

Supersonic Concepts

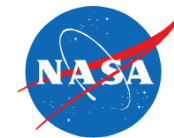
New Engine Integration Concepts Symposium



Mike Park
Sriram Rallabhandi
Christopher Heath
Irian Ordaz
NASA
August 24, 2017

Collaborative Research Center 880
Fundamentals of High Lift for Future Civil Aircraft
TU Braunschweig

Overcoming the Barriers to Practical High Speed Vehicles



Environmental Barriers

Sonic Boom

- Design for low noise sonic boom
- Understand community response

Airport Noise

- Noise levels not louder than subsonic aircraft at appropriate airports

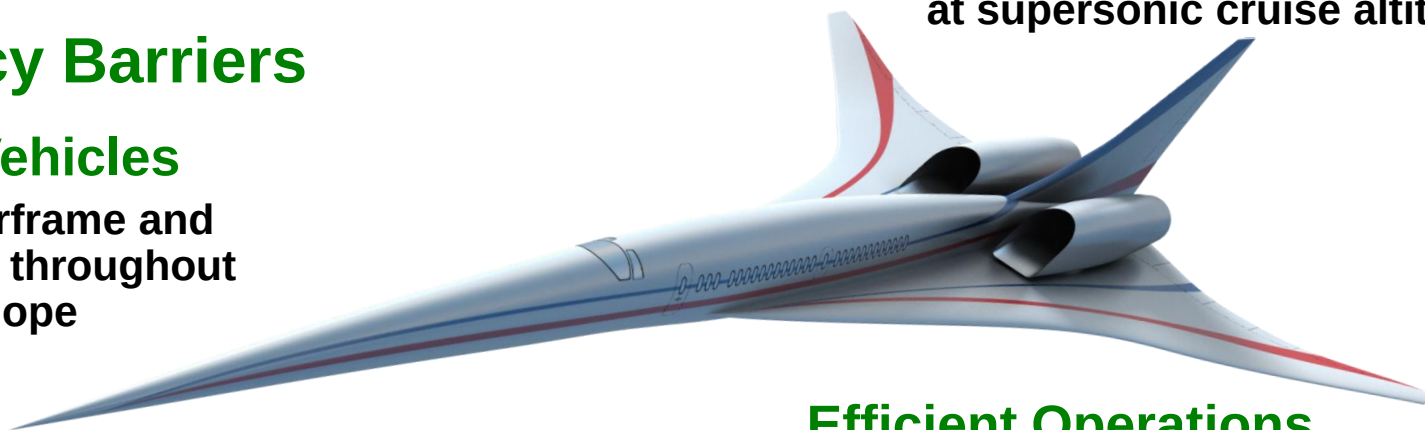
High Altitude Emissions

- No or minimal long term impact at supersonic cruise altitudes

Efficiency Barriers

Efficient Vehicles

- Efficient airframe and propulsion throughout flight envelope



Light Weight, Durable Vehicles

- Low airframe and propulsion weight in a slender flexible vehicle operating at supersonic cruise temperatures

Efficient Operations

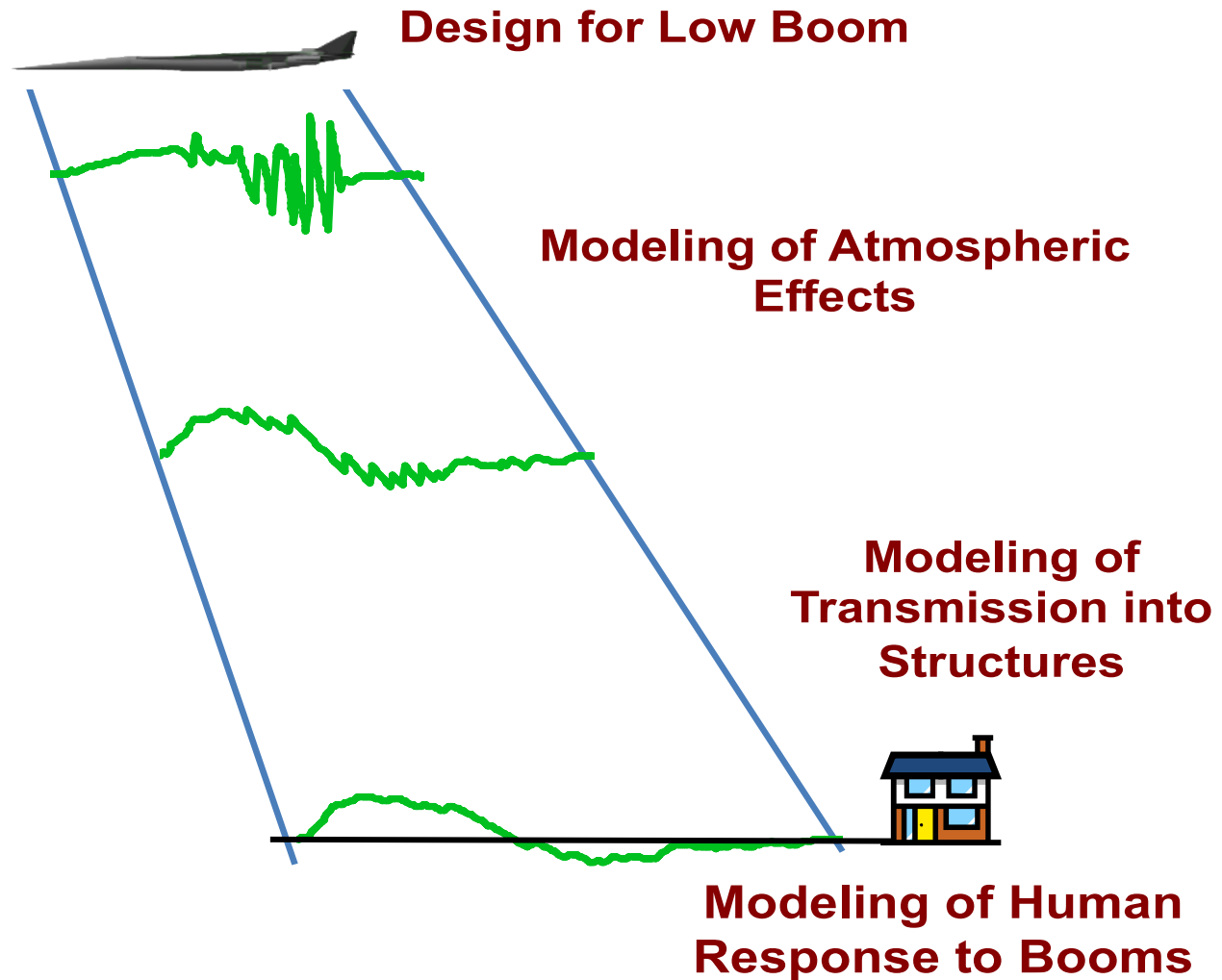
- Airspace-Vehicle interaction for full utilization of high speed

Solutions to Barriers Drive the Selection of NASA Research Themes

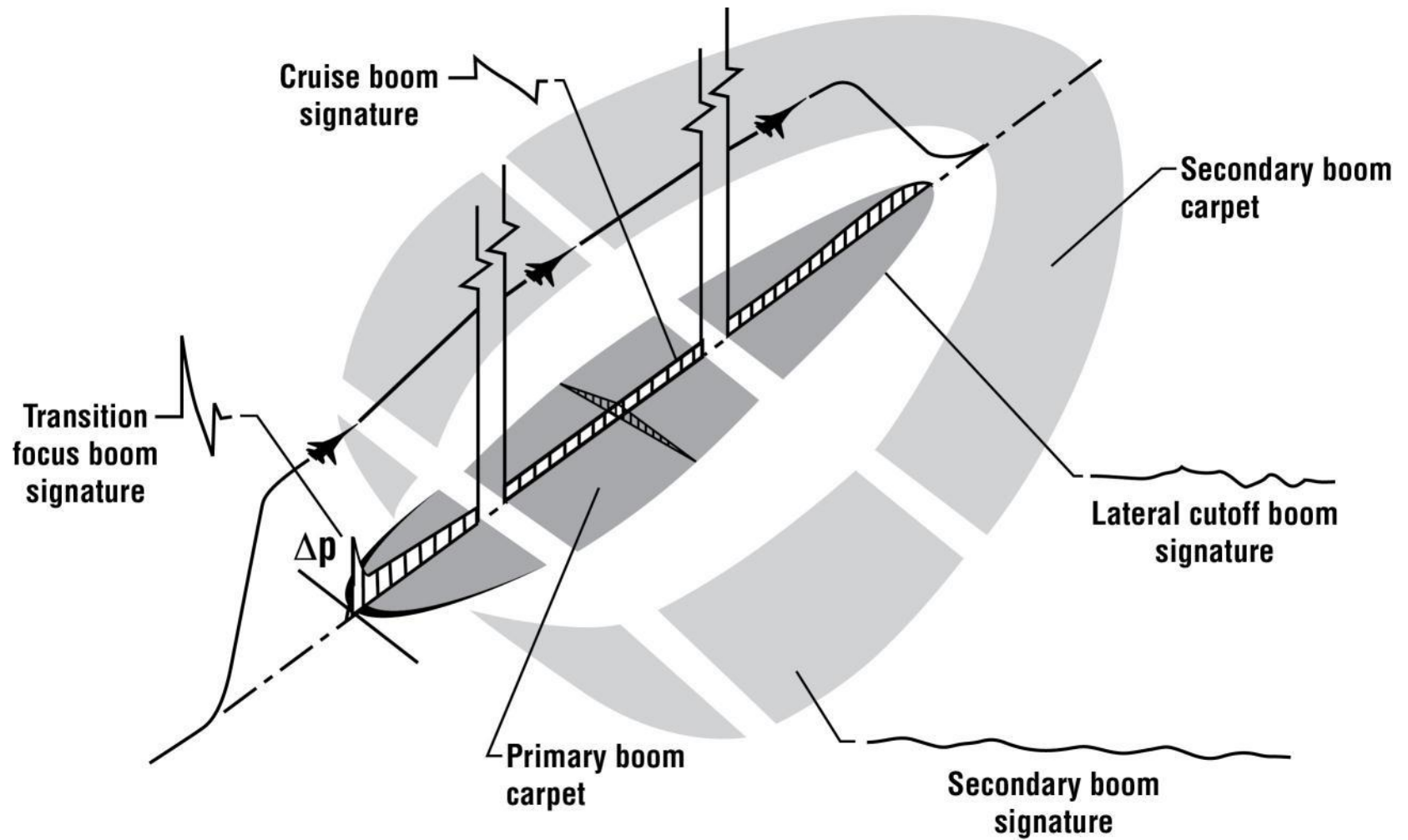
Overland Supersonic Flight



- Current prohibition is a significant barrier to opening new markets for supersonic civil aircraft
 - FAA: No flight at Mach > 1.0
 - ICAO: No sonic boom disturbance
- Foster a rule change driven by improved technology and industry interest to create a certification standard
- International cooperation is required
- Prediction variation and uncertainty needs to be quantified for a relevant vehicle



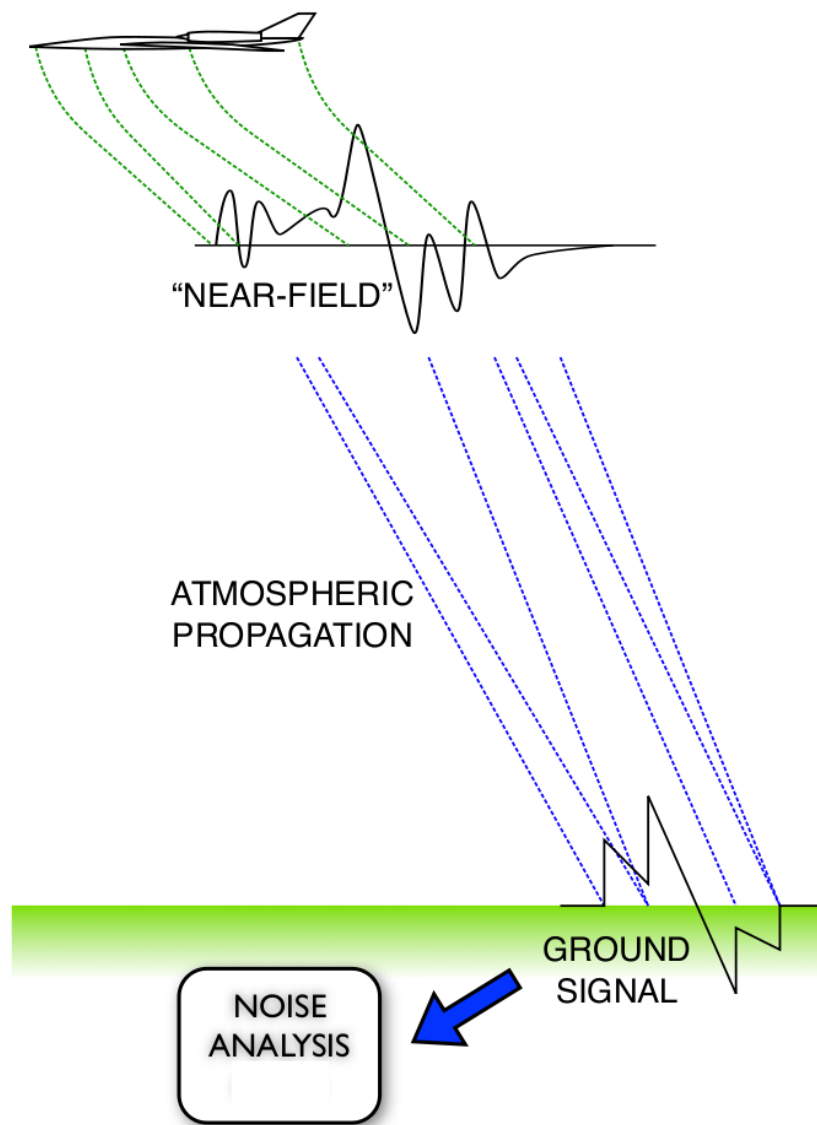
Typical Mission Boom Carpet



Prediction of Loudness (Annoyance)



- Generation of the acoustic disturbances
- Propagation through real atmosphere
 - Winds, temperature variation, molecular relaxation, turbulence, and aircraft maneuvers
- Response of structures (typically below 10 Hz)
- Perception of noise and annoyance correlated to noise measures through experiments
- Stevens JASA (1972) Perceived Level (PL)
- A-Weighted Sound Exposure Level (ASEL)

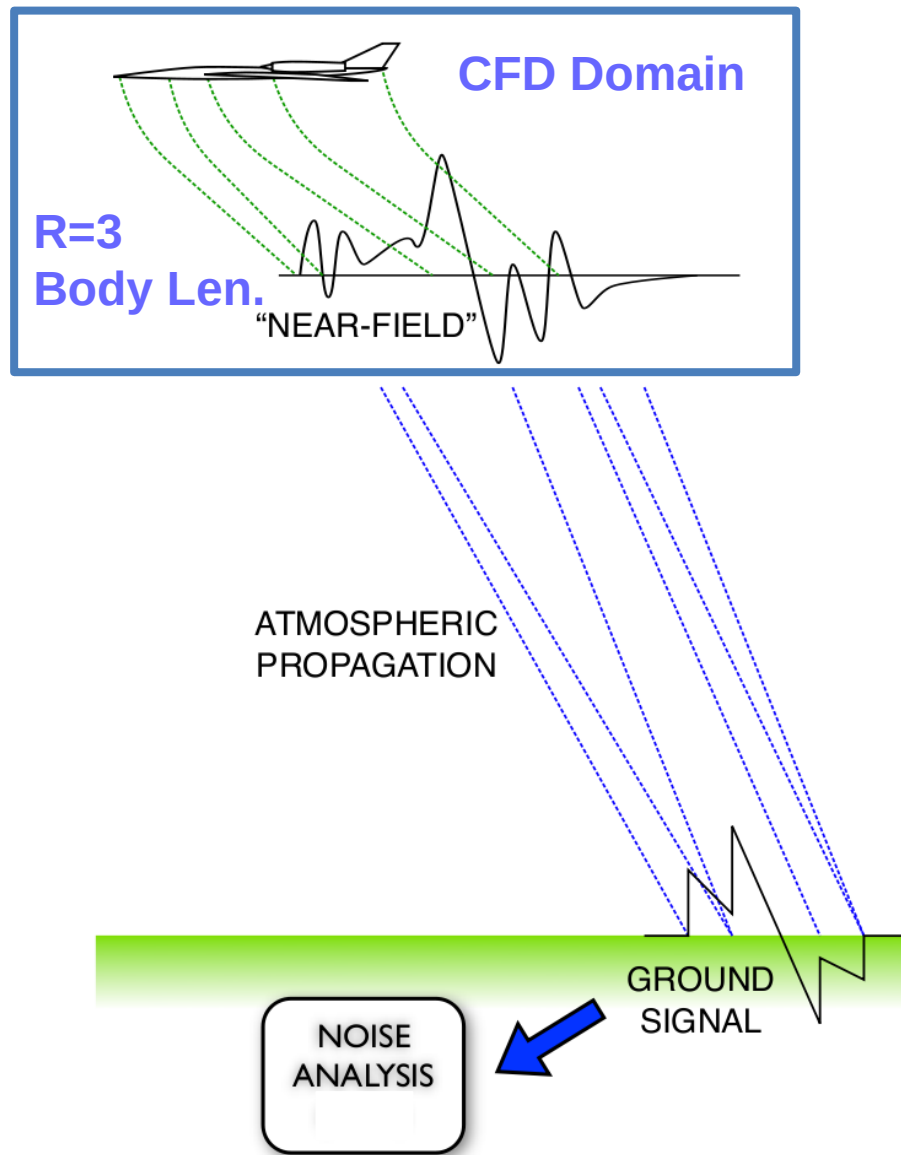


[Wintzer, PhD Thesis, Stanford, 2012]

Coupled Analysis and Sensitivity

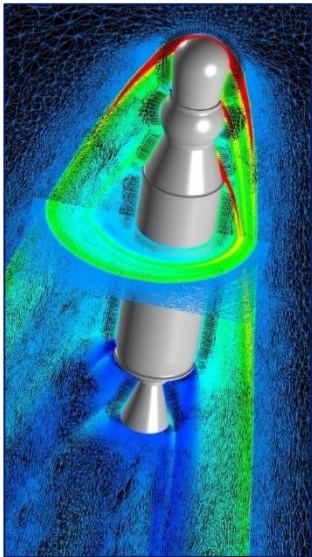
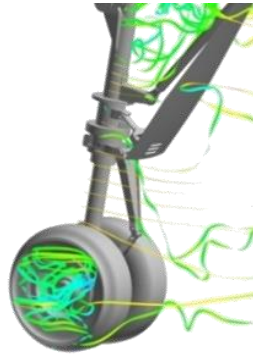
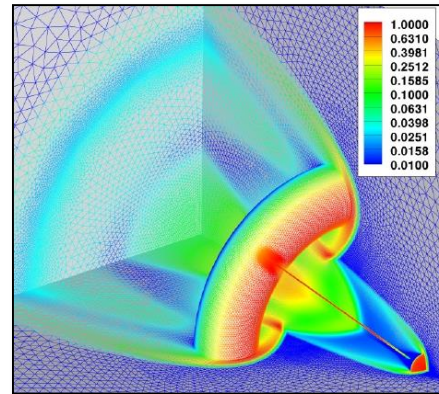
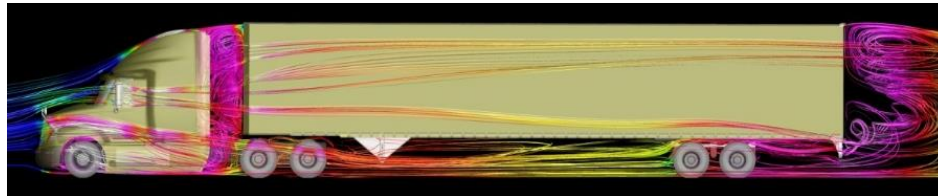
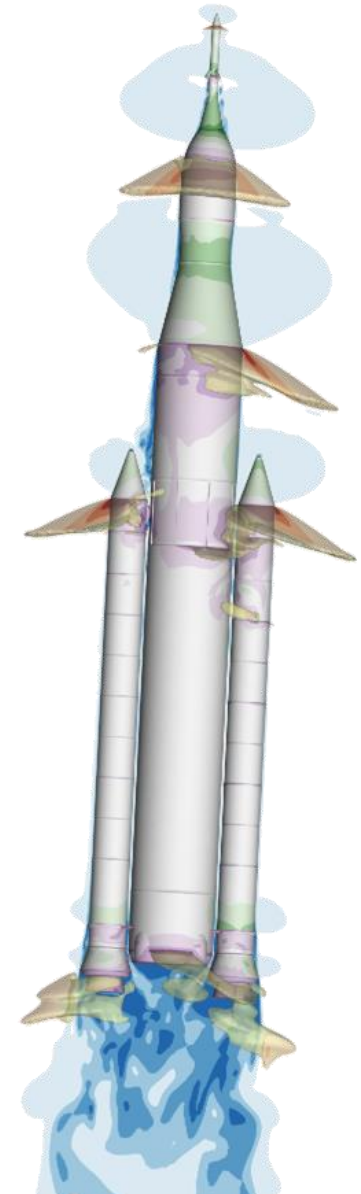


- General purpose Computational Fluid Dynamics (CFD) tool used near the configuration
 - Include propulsion effects
 - Structural and control effects possible (AIAA 2017-0040)



[Wintzer, PhD Thesis, Stanford, 2012]

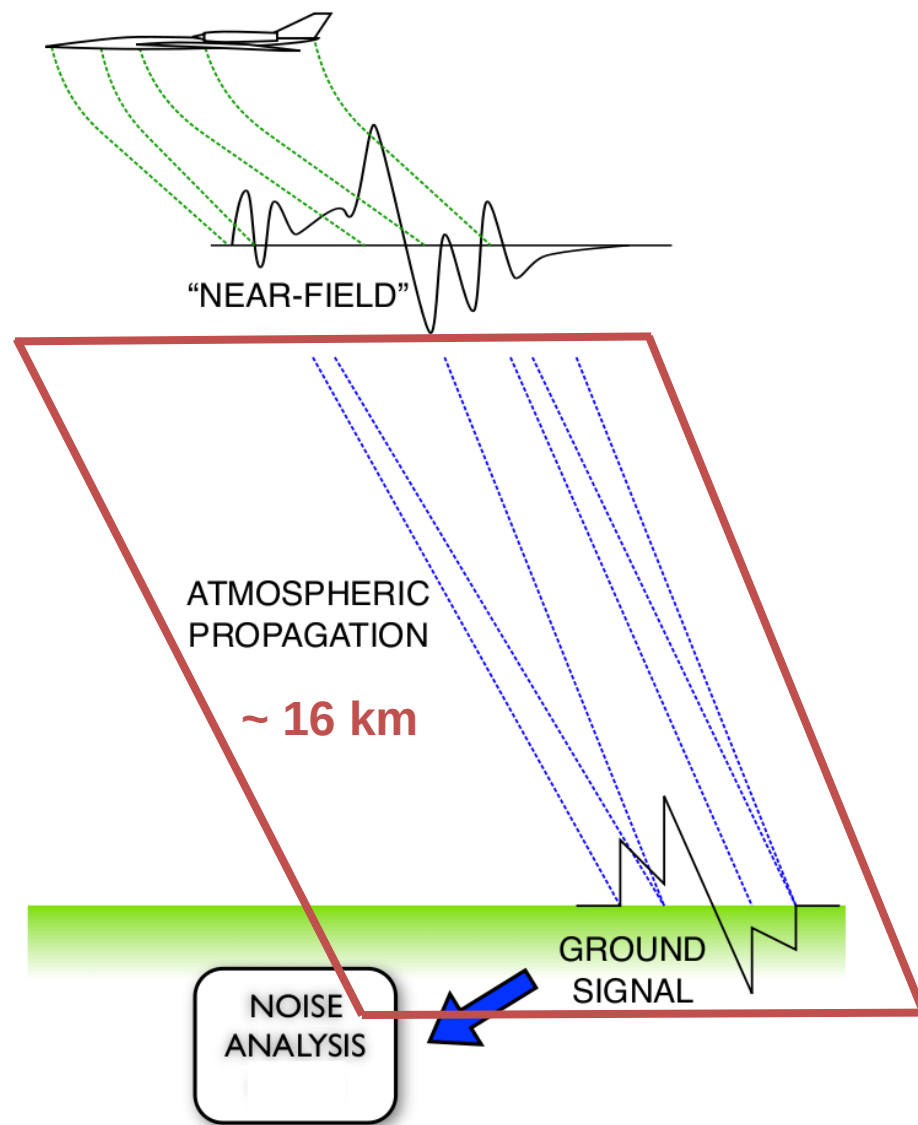
- Established as a research code in late 1980s; now supports numerous internal and external efforts across the speed range
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- General dynamic mesh capability: any combination of rigid / overset / morphing grids, including 6-DOF effects
- Aeroelastic modeling using mode shapes, full FEM, CC, etc.
- Constrained / multipoint adjoint-based design, mesh adaptation
- Distributed development team using agile/extreme software practices including 24/7 regression, performance testing
- Limited release to US Persons



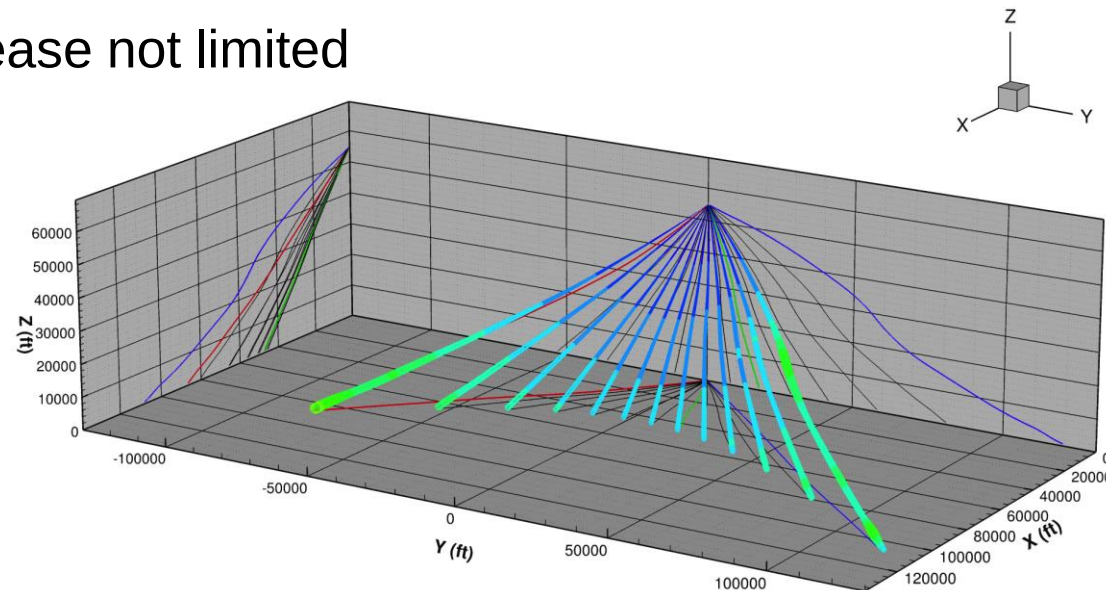
Coupled Analysis and Sensitivity



- General purpose Computational Fluid Dynamics (CFD) tool used near the configuration
 - Include propulsion effects
 - Structural and control effects possible (AIAA 2017-0040)
- Coupled to an atmospheric propagation code
 - Include winds, temperature variation, molecular relaxation
 - Intended for long propagation distances



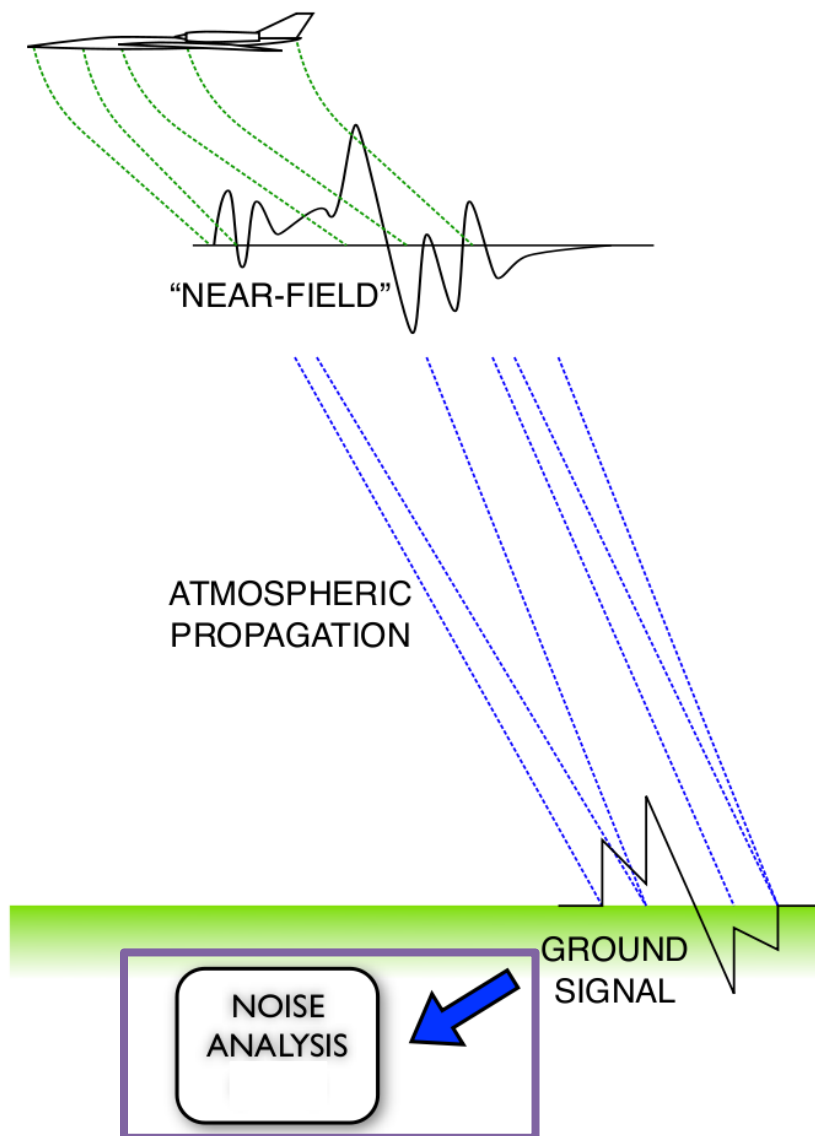
- Propagation based on lossy Burgers equation (AIAA 2011-1278)
 - Under-track, off-track signatures, horizontally stratified winds, acceleration, turn-rates, climb-rates
- Adjoint-based design capability (AIAA 2012-3220)
 - Near-field dp/p matching
 - Ground loudness optimization / target matching / equivalent area matching
 - Target equivalent area generation
 - Atmospheric sensitivities
- Adjoint release limited to US Person
- Propagation release not limited



Coupled Analysis and Sensitivity



- General purpose Computational Fluid Dynamics (CFD) tool used near the configuration (FUN3D)
 - Include propulsion effects
 - Structural and control effects possible (AIAA 2017-0040)
- Coupled to an atmospheric propagation code (sBOOM)
 - Include winds, temperature variation, molecular relaxation
 - Intended for long propagation distances
- A-Weighted Sound Exposure Level (ASEL)
 - Continuous formulation that can be evaluated in frequency and time domains
 - Differentiable PL Surrogate

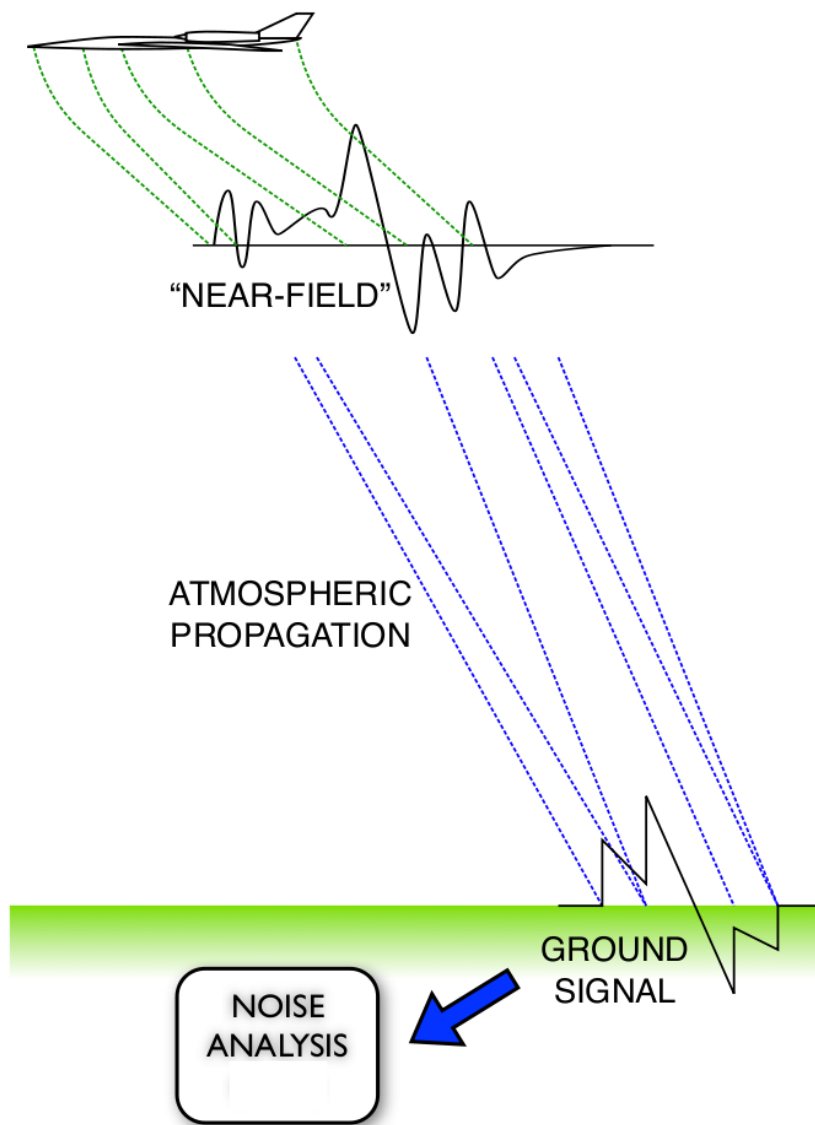


[Wintzer, PhD Thesis, Stanford, 2012]

Coupled Analysis and Sensitivity



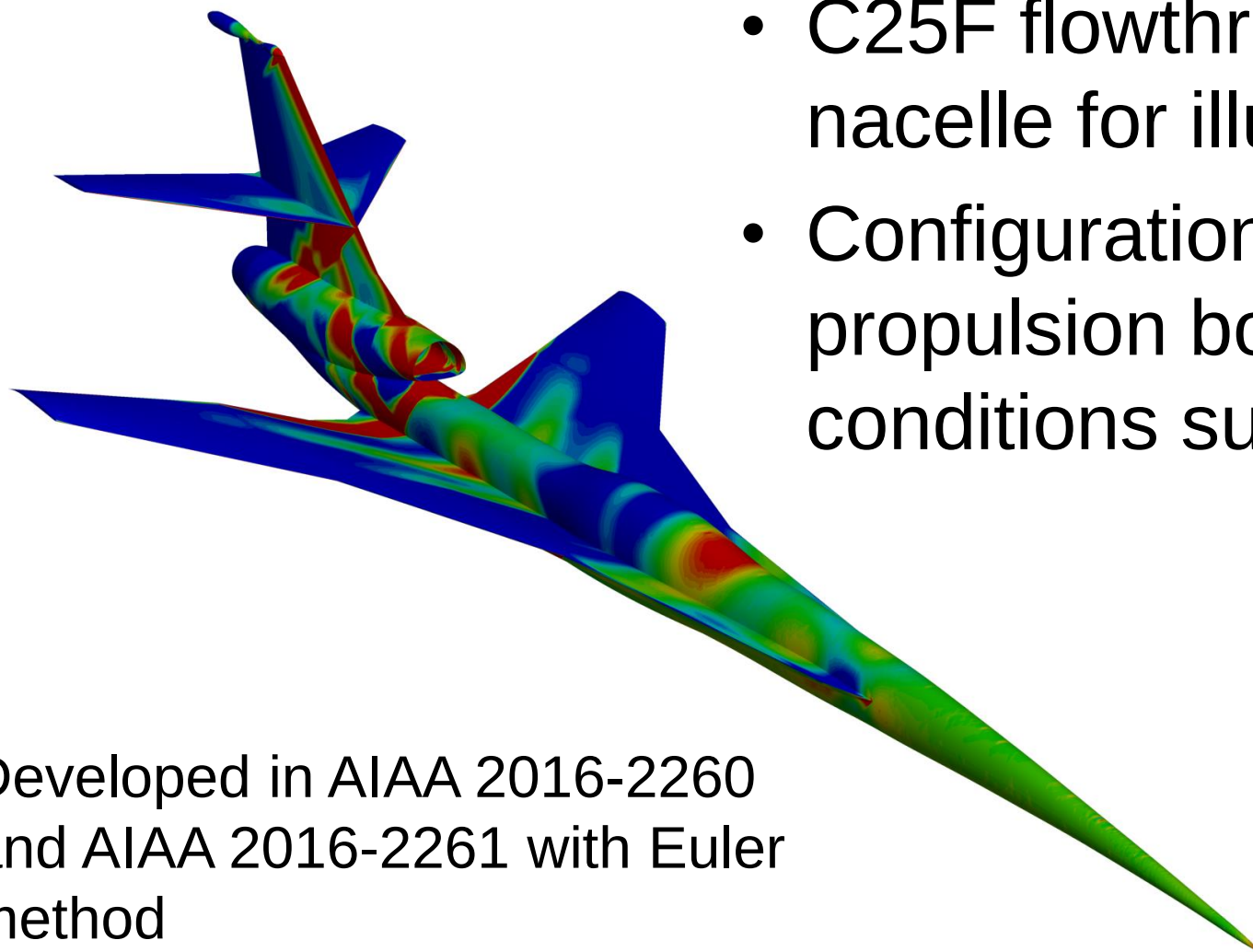
- The entire tool chain has been differentiated for error propagation, grid adaptation, and design
 - Forward sensitivities via complex step derivatives (AIAA 2017-0076)
 - Reverse sensitivities via discrete adjoint method (AIAA 2012-3220)
- Sonic boom workshops held at in conjunction with AIAA (American Institute of Aeronautics and Astronautics) conference assess nearfield Computational Fluid Dynamics (CFD) and the atmospheric propagation tools as part of sonic boom prediction (AIAA 2017-3256 and AIAA 2017-3257)



[Wintzer, PhD Thesis, Stanford, 2012]

- Propagating estimated CFD truncation error with complex valued FUN3D and sBOOM to estimate impact on CFD pressure, ground signature, and ASEL (AIAA 2017-0076)
- Coupled FUN3D and sBOOM adjoint to compute sensitivity of ASEL to geometry perturbations (AIAA 2012-3220)
- Design isolated multistream nozzle to reduce impact on signature and maintain efficiency (AIAA 2015-1047)
 - Adjoint-based grid adaptation required to capture the exhaust plume
- Design aft signatures of a powered concept to recover a target pressure signature in the nearfield (AIAA 2017-3046)
- Design inlet geometry to reduce circumferential distortion (AIAA 2017-3410)
 - Adjoint-based grid adaptation required to capture the distortion
- Quantify the international state of the art in nearfield CFD for sonic boom prediction via workshop (AIAA 2017-3256)

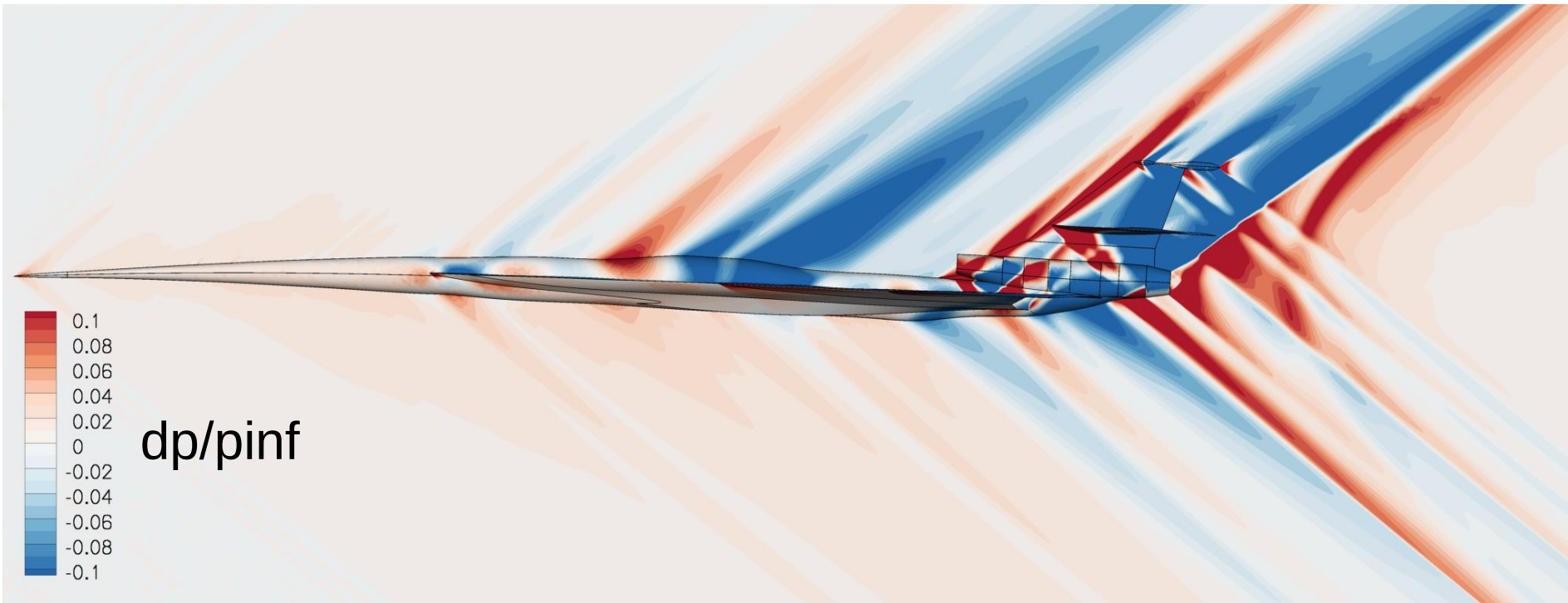
C25F Low-Boom Demonstrator Concept



- C25F flowthrough nacelle for illustration
- Configurations with propulsion boundary conditions supported

Developed in AIAA 2016-2260
and AIAA 2016-2261 with Euler
method

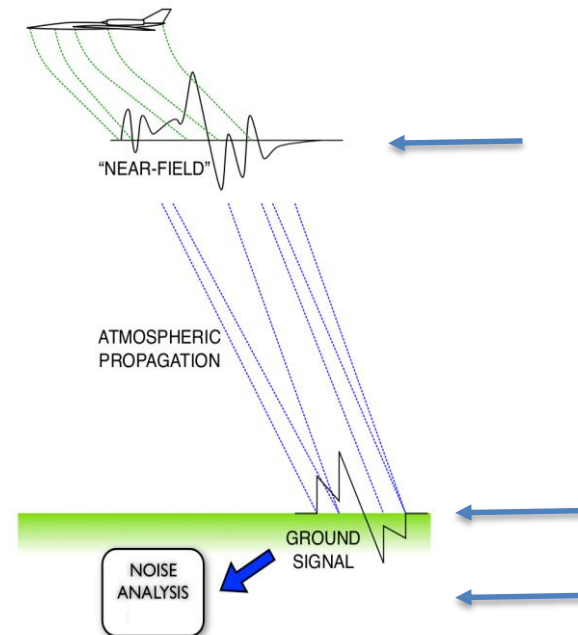
C25F Pressure Disturbance



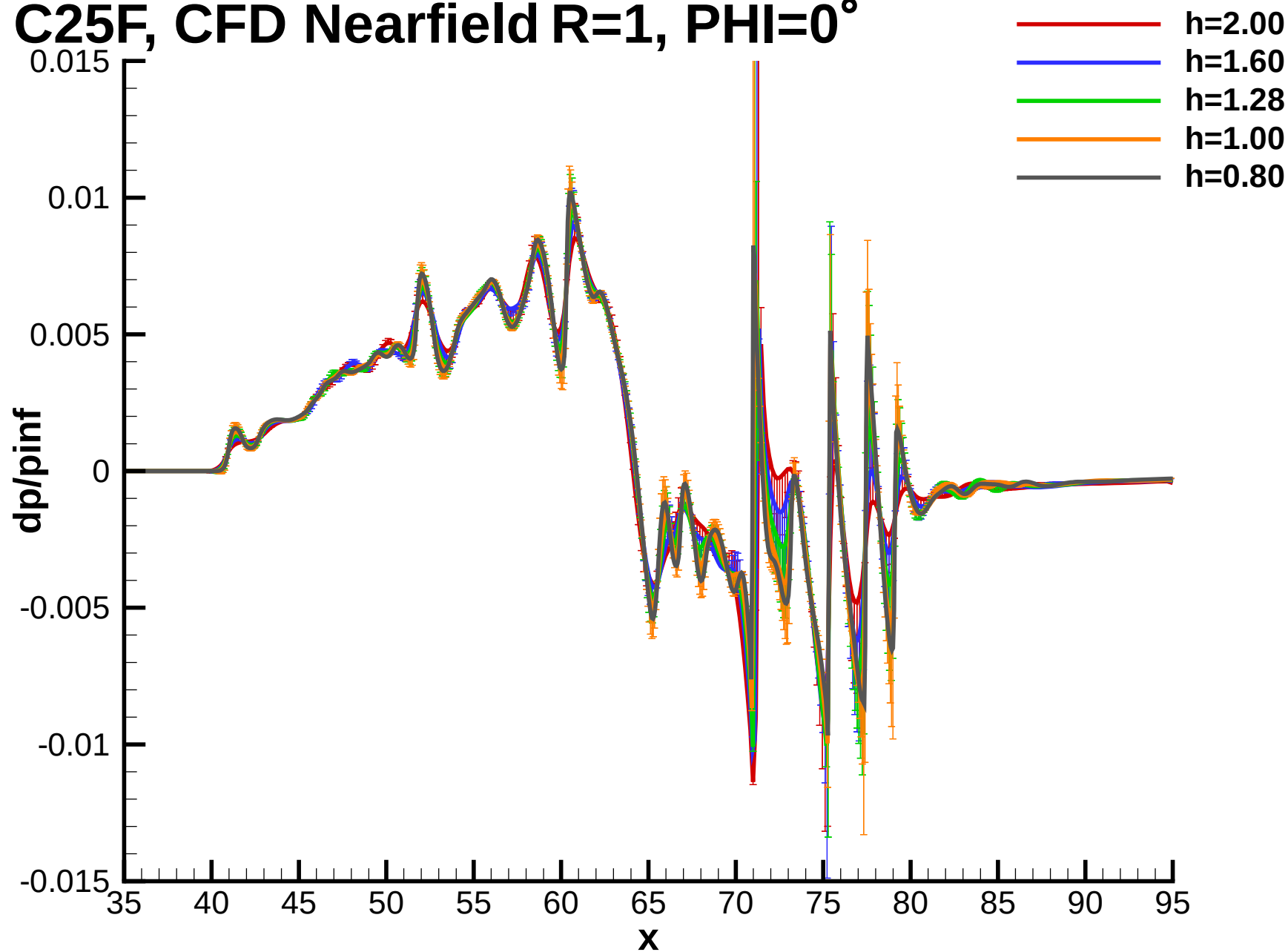
Error Transport Equation (AIAA 2017-0076)



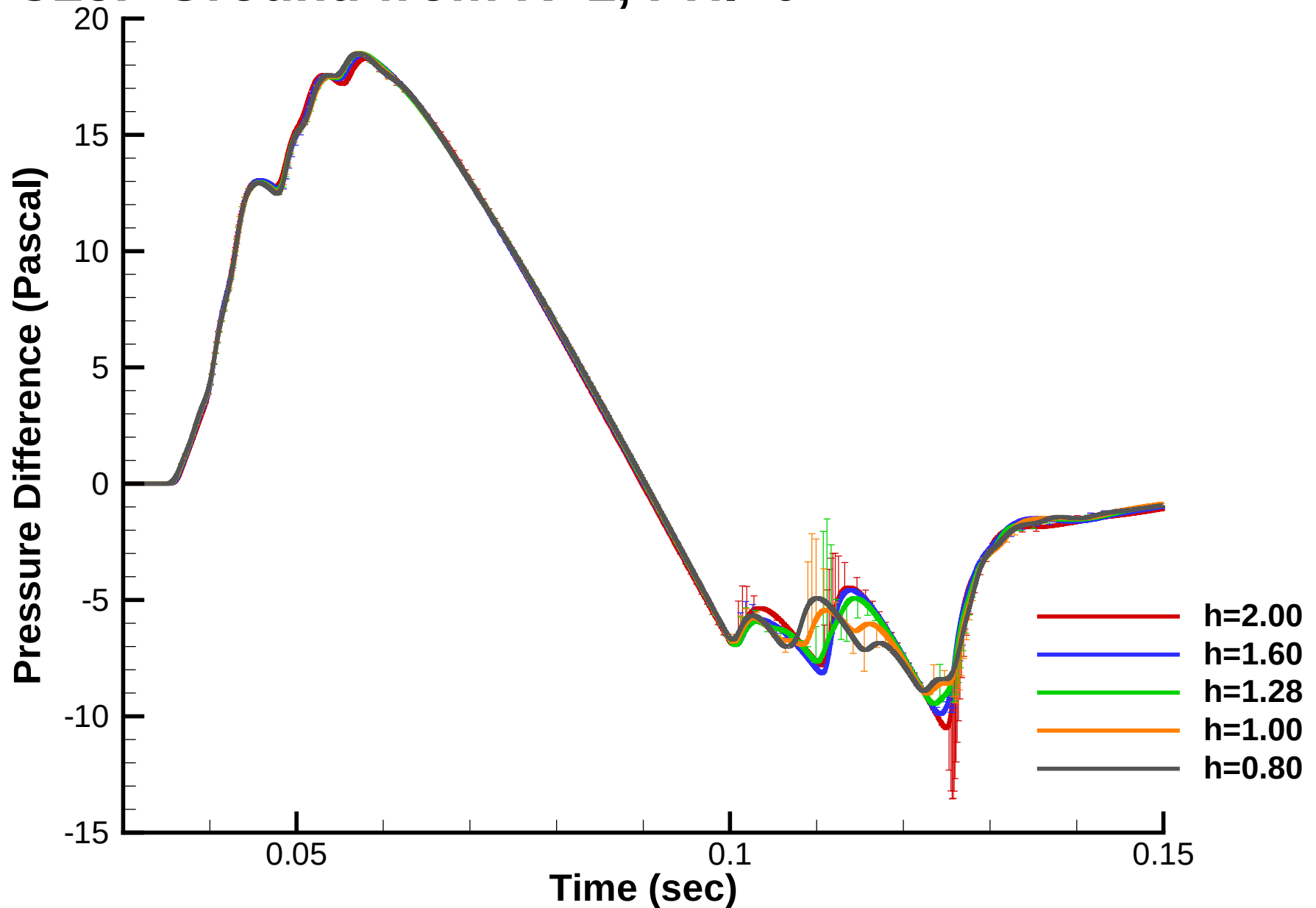
- Estimate truncation error by interpolating the solution to a finer, embedded grid and evaluating the residual
- Propagate truncation error as an imaginary source term to a complex valued flow solver to compute discretization error
- Linearized impact of uniform grid refinement at the cost of a complex solution on the current grid
- Discretization error estimate provided for entire solution and output quantities
 - Displayed as one-sided error bars



C25F, CFD Nearfield R=1, PHI=0°

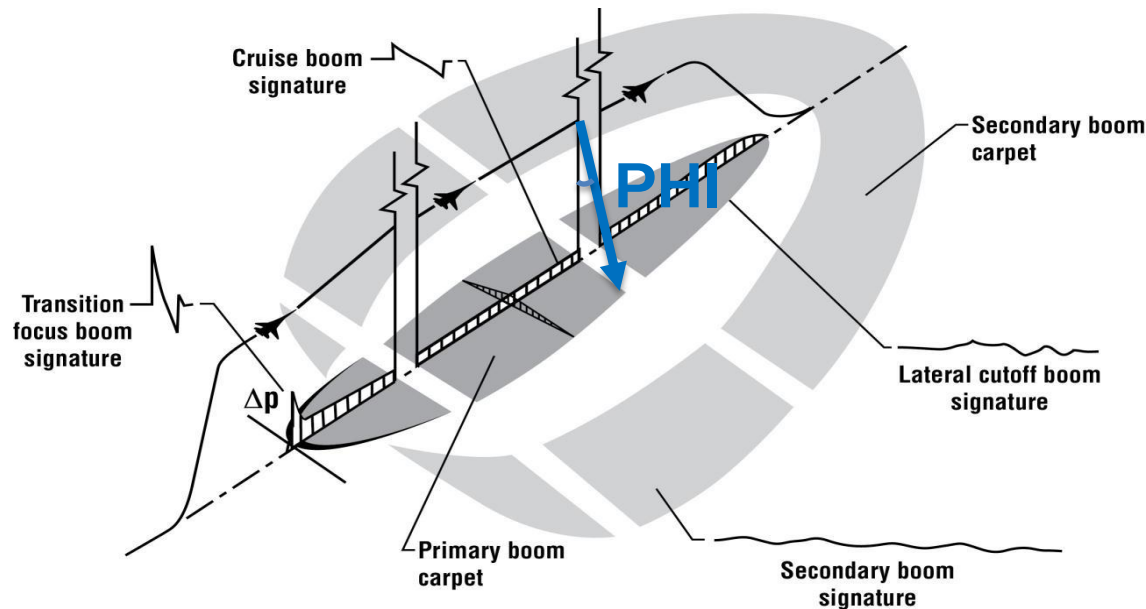
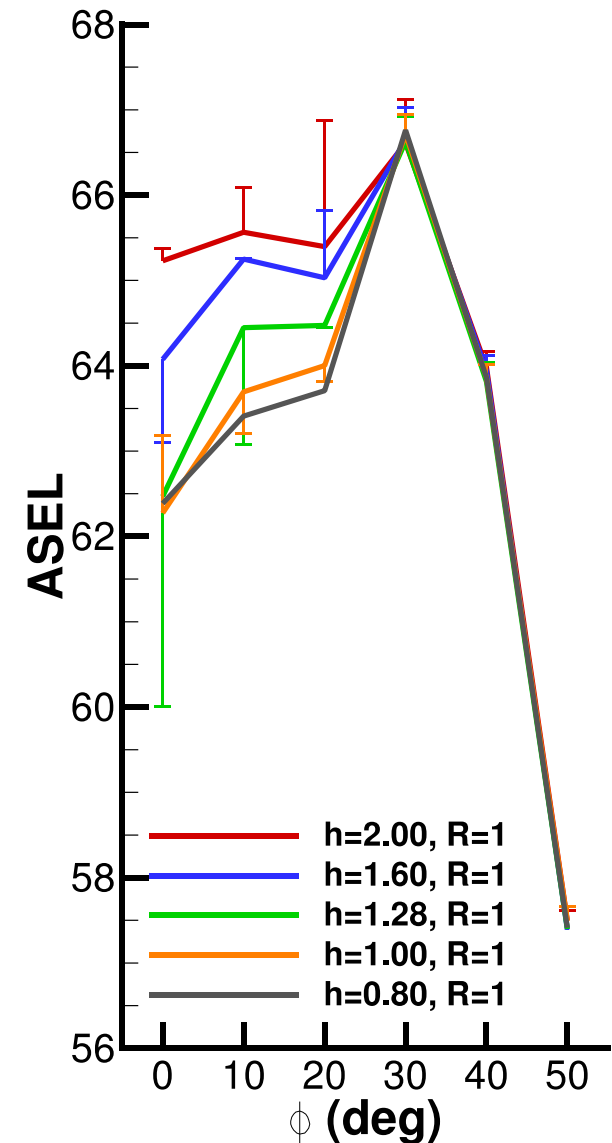


C25F Ground from R=1, PHI=0°

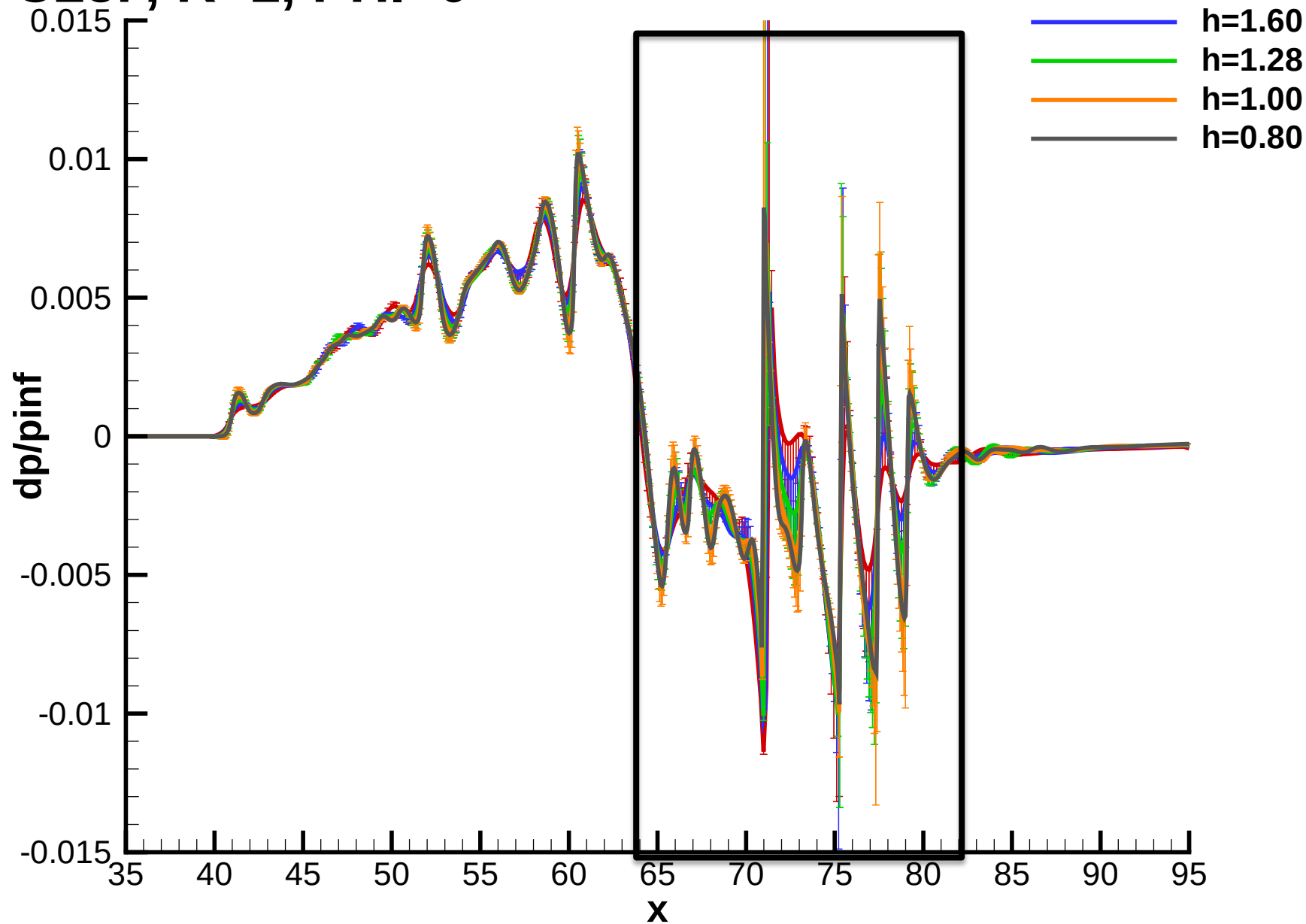


C25F ASEL Carpets (AIAA 2017-0076)

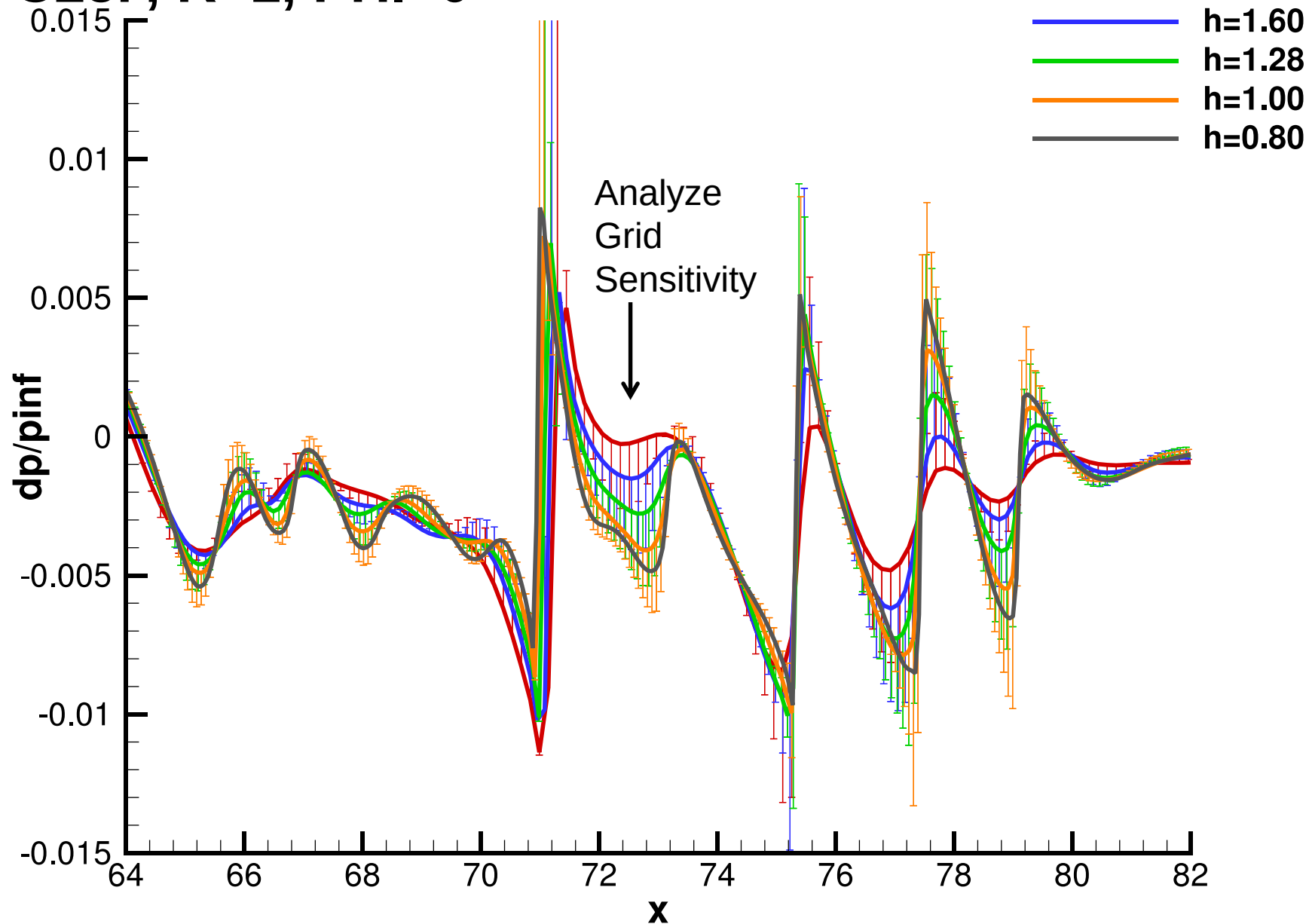
- Single CFD solution with multiple nearfield extraction locations and atmospheric propagation calculations



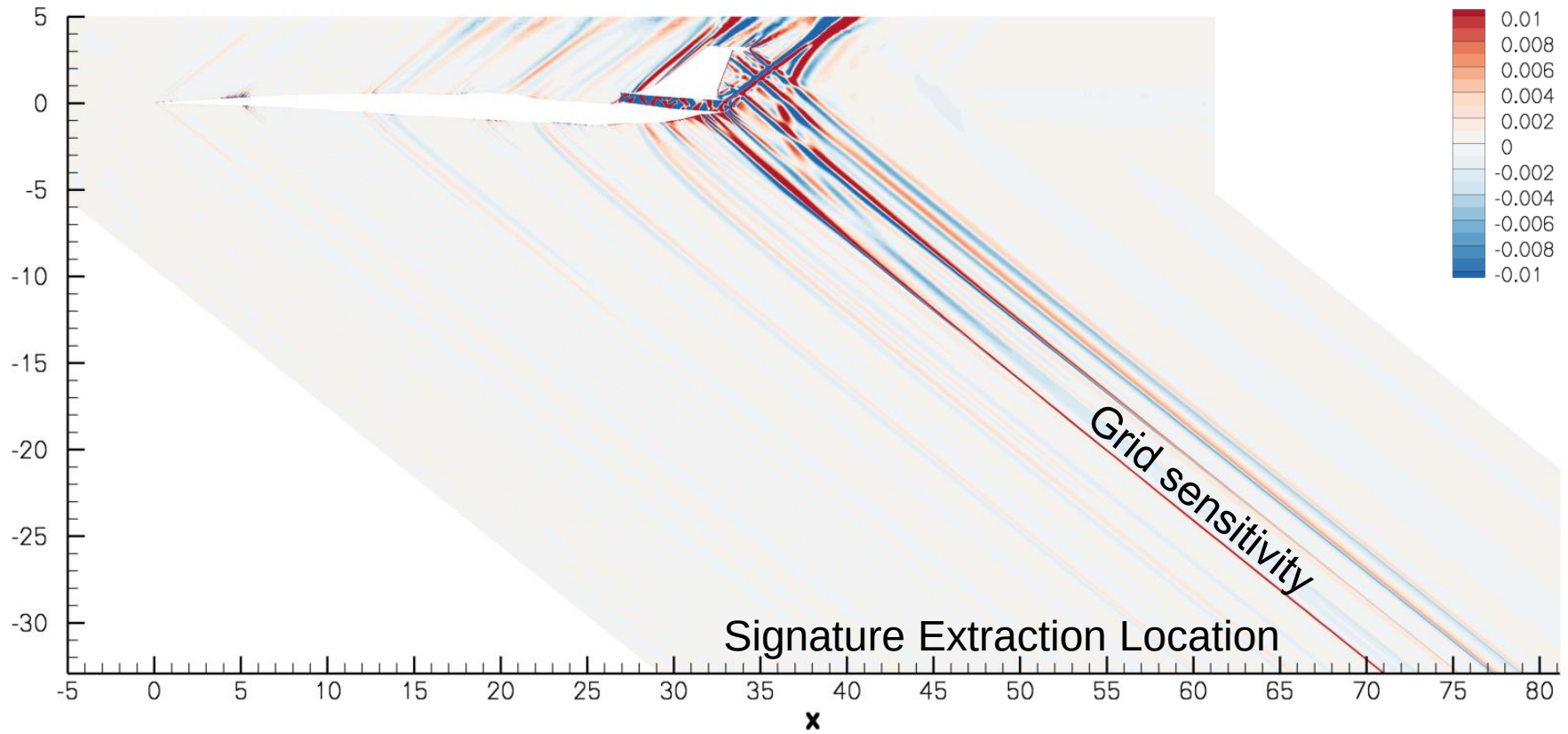
C25F, R=1, PHI=0°



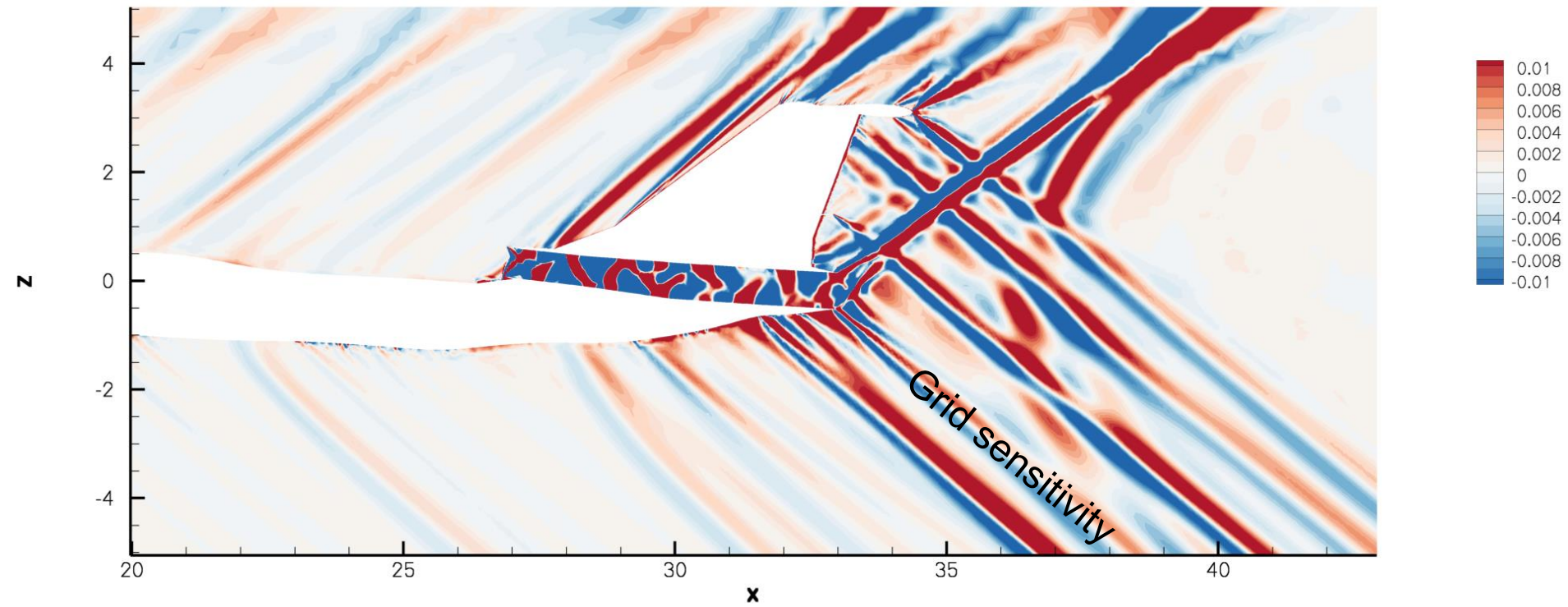
C25F, R=1, PHI=0°



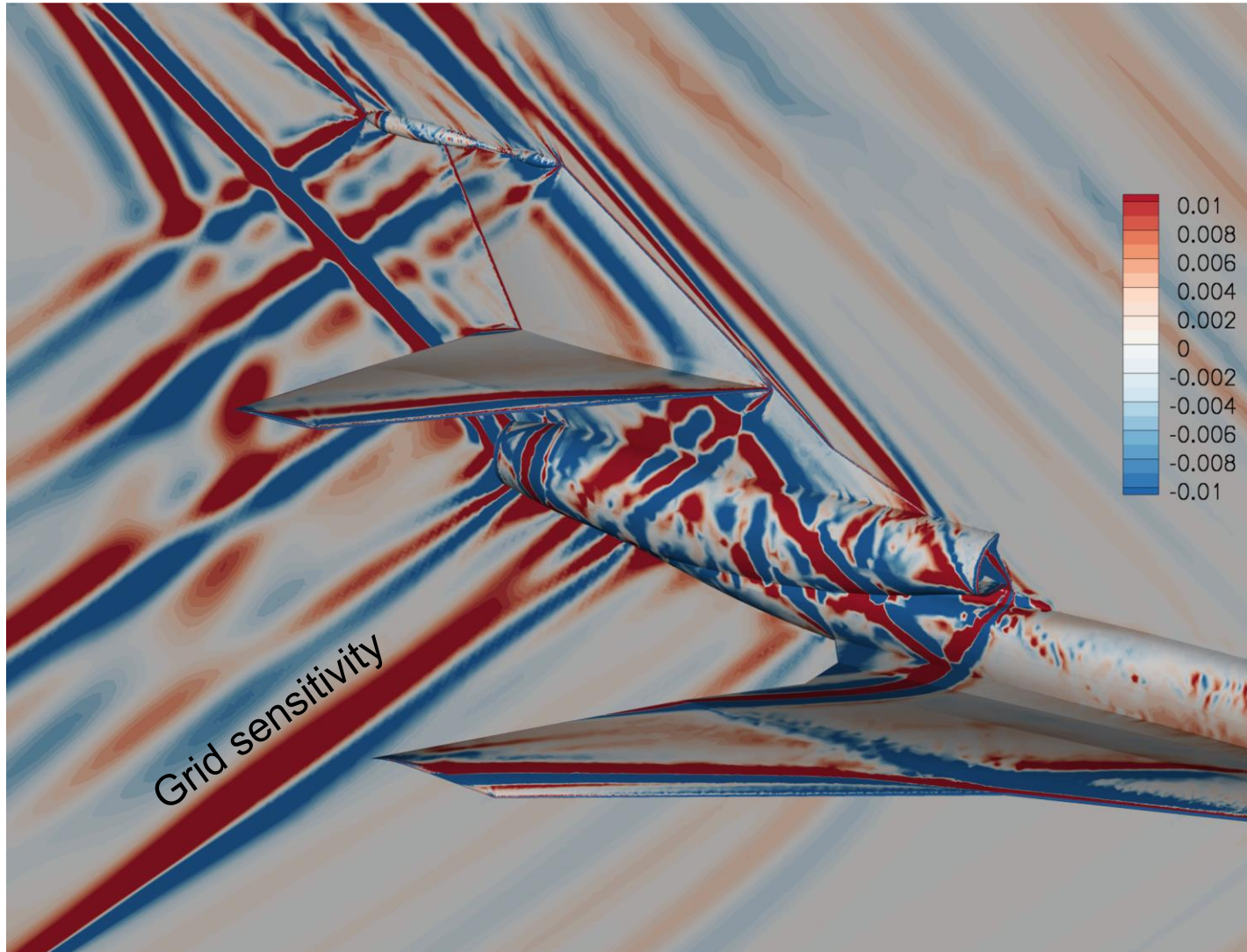
C25F $\Delta p/p_\infty$ Error



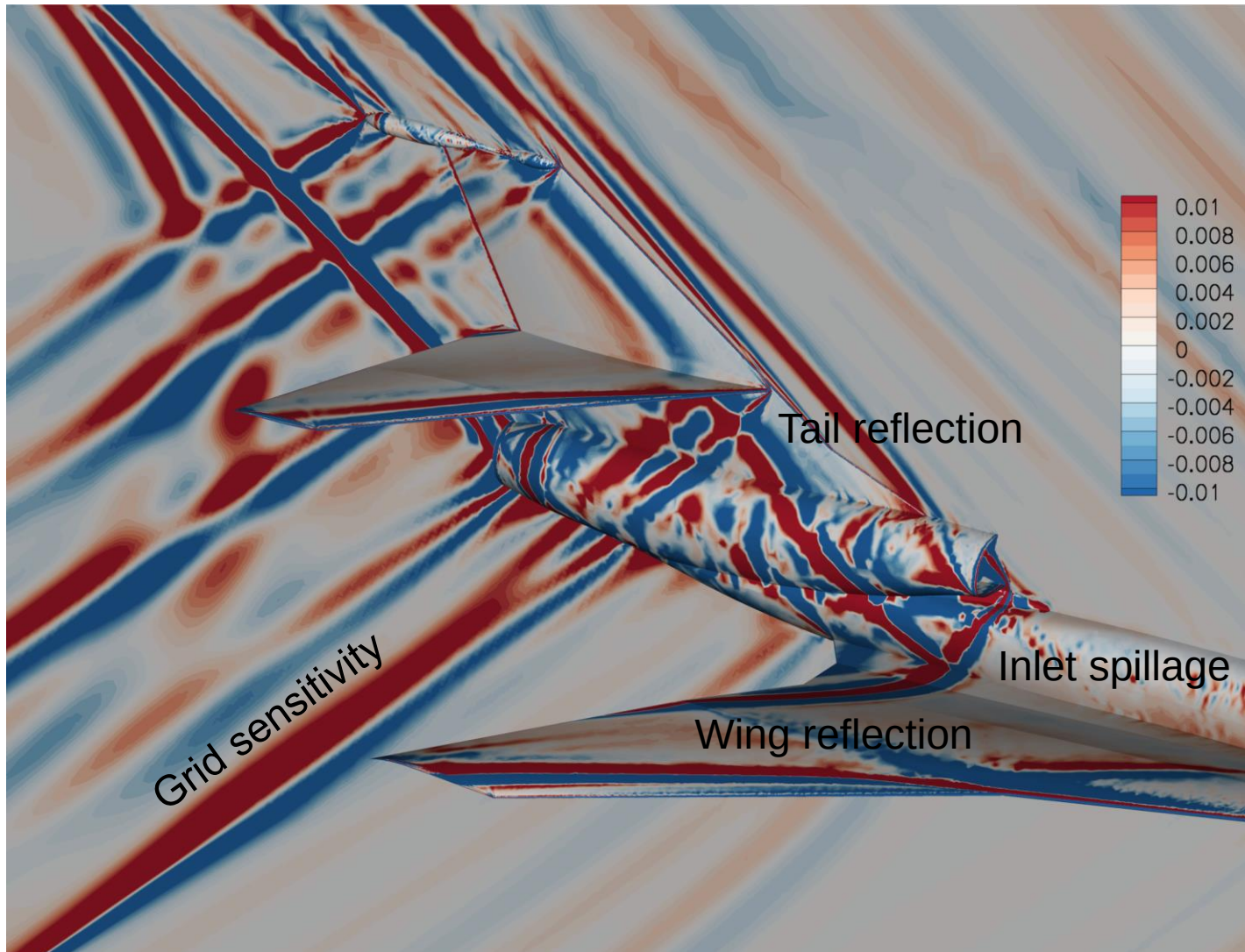
C25F $\Delta p/p_\infty$ Error



C25F $\Delta p/p_\infty$ Error



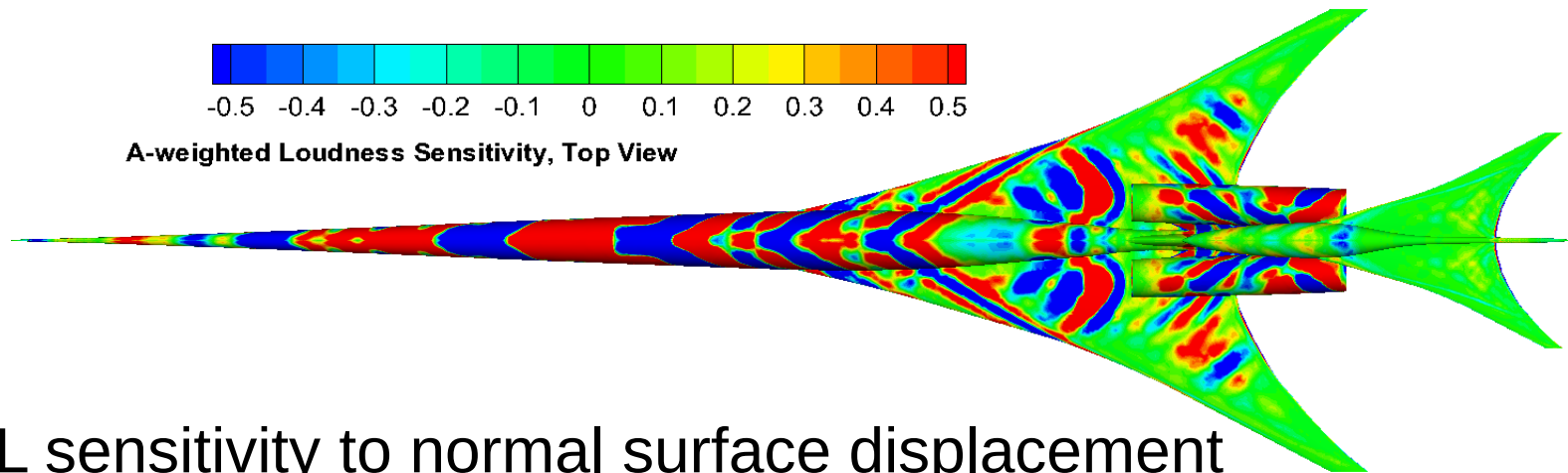
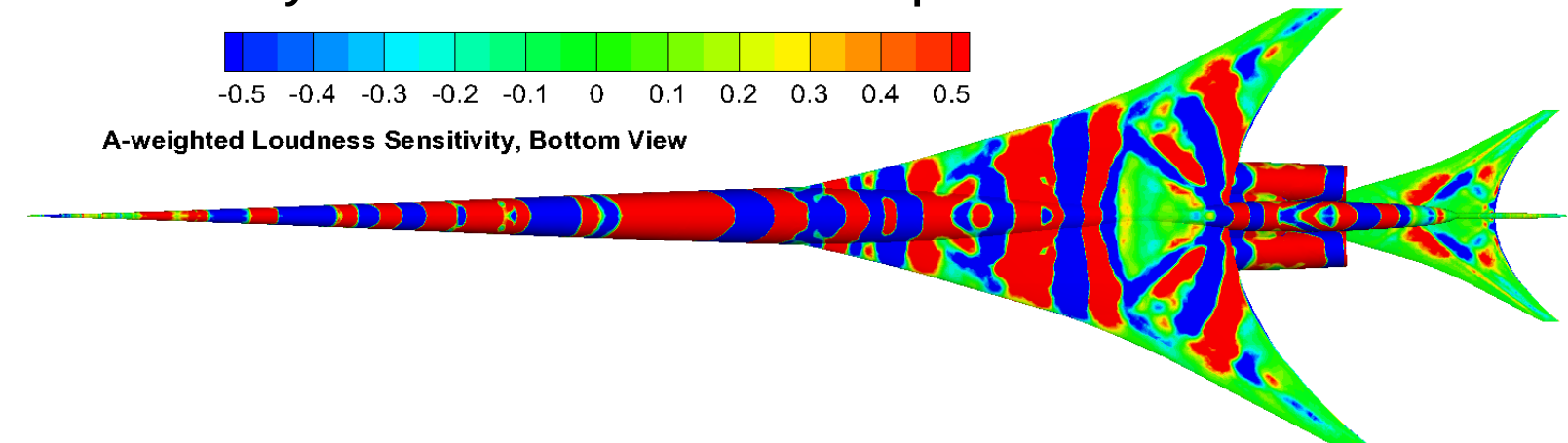
C25F $\Delta p/p_\infty$ Error



Adjoint Sensitivities



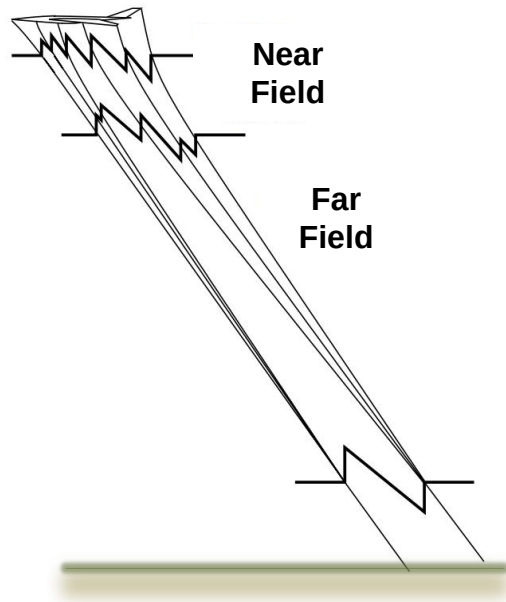
- A discrete adjoint is available for the entire tool chain provides output sensitivities for design (AIAA 2012-3220) and grid adaptation (AIAA 2017-3049)



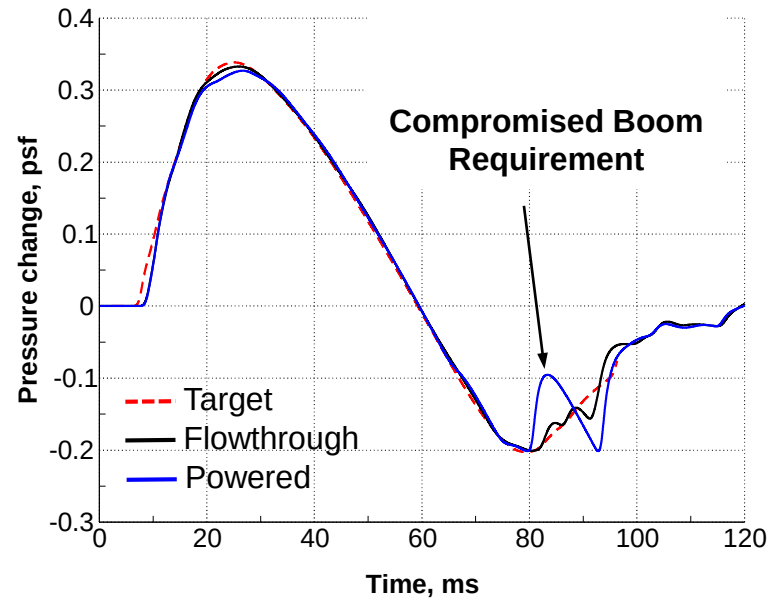
Propulsion Integration and Sonic Boom AIAA 2015-1047



Overland sonic boom requirements challenge supersonic aircraft viability



Propagated Ground Signature*



Current State-of-the-Art:

Aerodynamic shape optimization demonstrated with airframe tailoring to meet low-boom perceived loudness goals

Drawbacks:

Recent experimental and computational research has shown introducing propulsion effects into an optimized airframe pressure signature can compromise the low-boom requirement (AIAA 2015-1045)

**Mitigate plume-induced near field pressure disturbances
without compromising isolated nozzle performance**

Initial Approach:

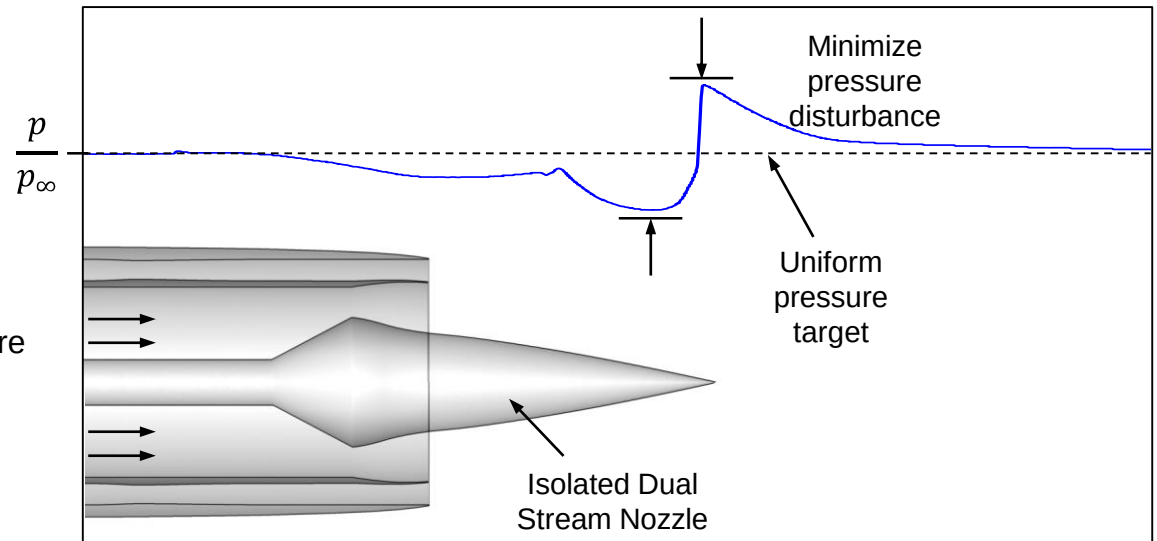
Aerodynamic tailoring of the powered propulsive streamtube to **minimize** all nearfield pressure contributions and simplify propulsion-airframe integration

Minimize:

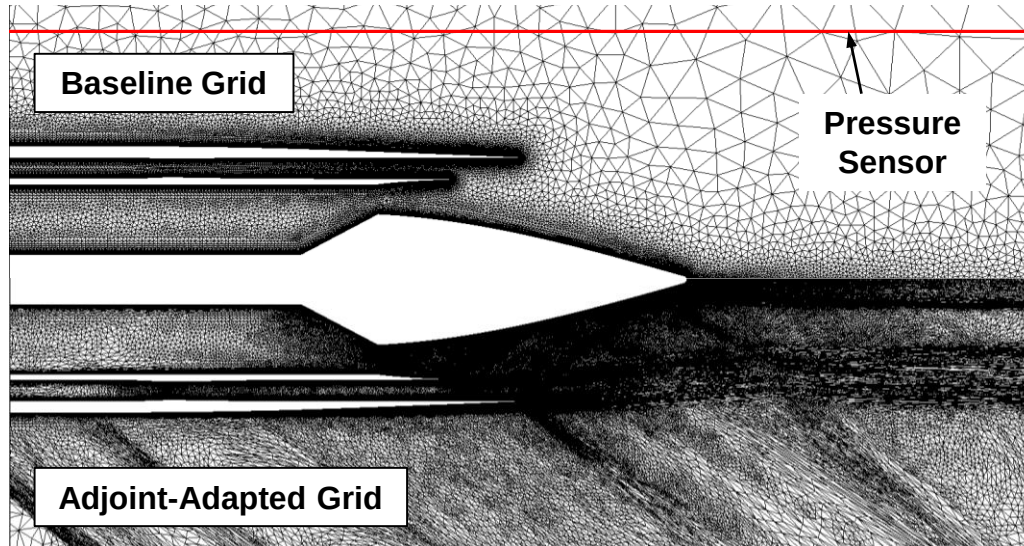
$$f = \sum_{i=1}^N \left(\frac{p}{p_{\infty}} \Big|_i - \frac{p}{p_{\infty}} \Big|_i^* \right)^2$$

Local pressure ratio

Target pressure ratio = 1



Adjoint-Based Grid Refinement AIAA 2015-1047

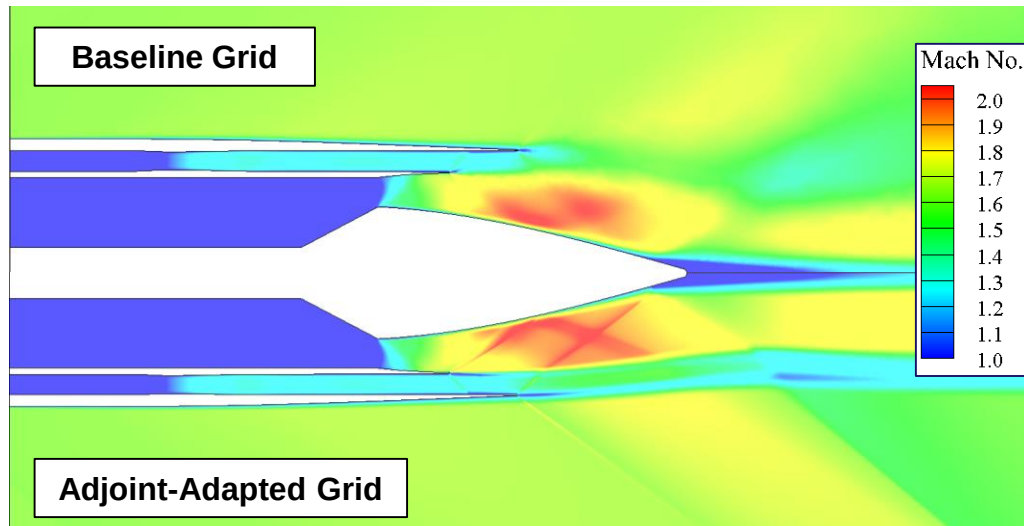


Baseline Grid:

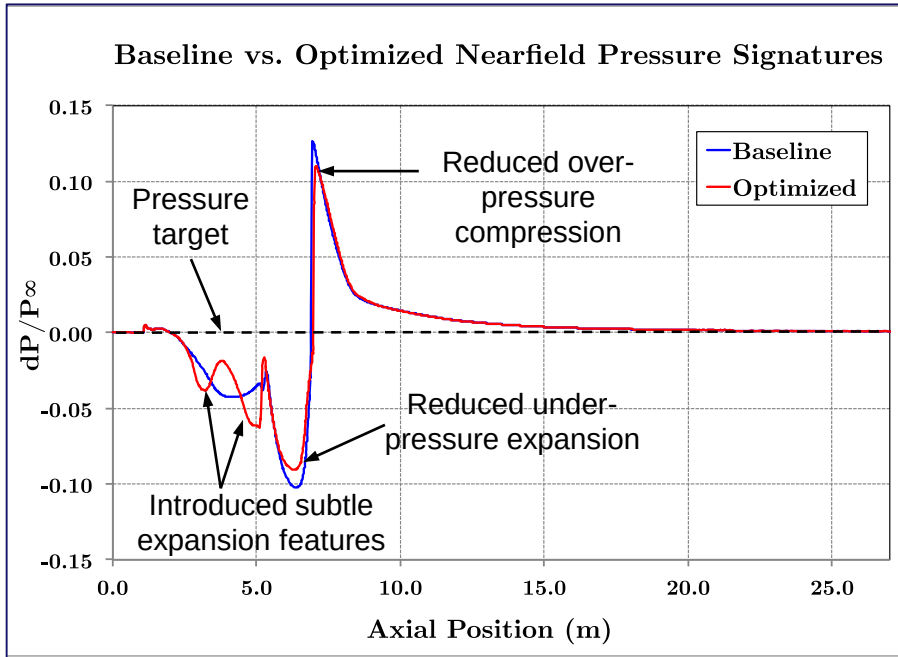
- ~3.5 million nodes
- Fully unstructured 2-D and 3-D T-rex viscous grid transitioning to isotropic tets in farfield ($y^+ < 1$)

Adjoint-Adapted Grid:

- Adapted to minimize discretization error of pressure integral extracted one nozzle diameter from centerline
- 8 flow/adjoint adaptation cycles
- ~11.5 million nodes
- Constraints used to control maximum anisotropy and grid size during adaptation
- Consumed ~36-hrs on 600 cores

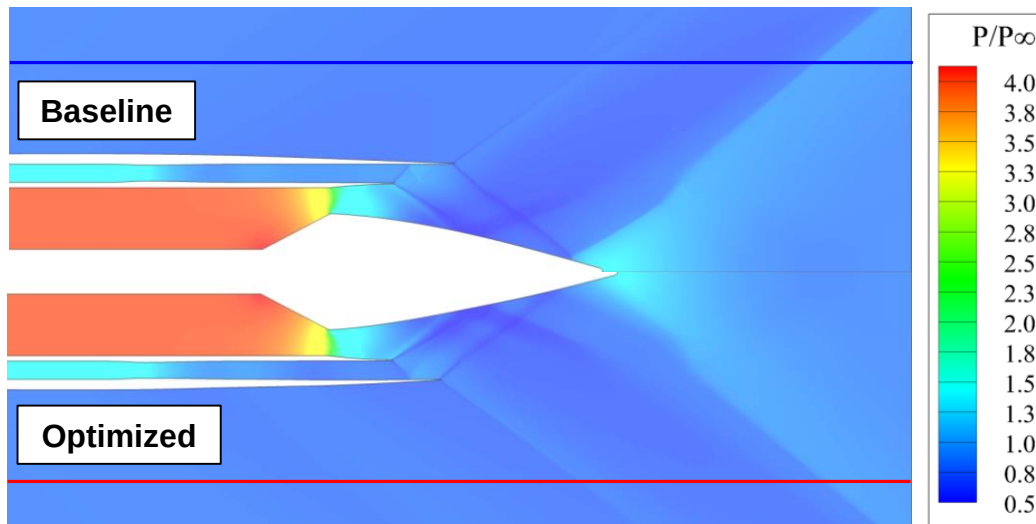


Adjoint-Based Design Optimization AIAA 2015-1047



Component	Thrust (N) Baseline	Δ Thrust (N) Optimized
Bypass Inflow	26478	+5
Core Inflow	96228	-10
Inner Cowl	-1347	-10
Outer Cowl	-1525	-27
Inner Shroud	1505	+31
Outer Shroud	-1158	-32
Centerbody	-32121	+207
Total	88059	+175

~0.2% Thrust Increase



Drag-Constrained Low-Boom Design (AIAA 2017-3046)

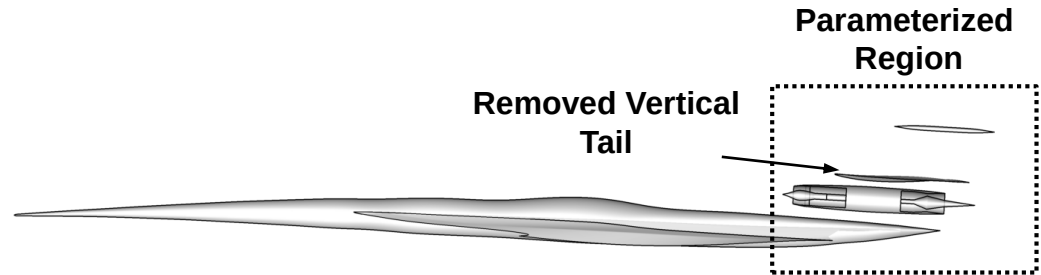


Design Vars. – 48 Total

- Vertical Tail Fairing – 9 DVs
- Engine OML – 9 DVs
- Nozzle Plug – 5 DVs
- Horizontal Tail – 21 DVs
 - Planform
 - Camber
 - Twist
 - X-Section
- Fuselage – 4 DVs

Optimizer

- Gradient-Based
- Leverage adjoint-based design approach
- Provide analytic surface derivatives



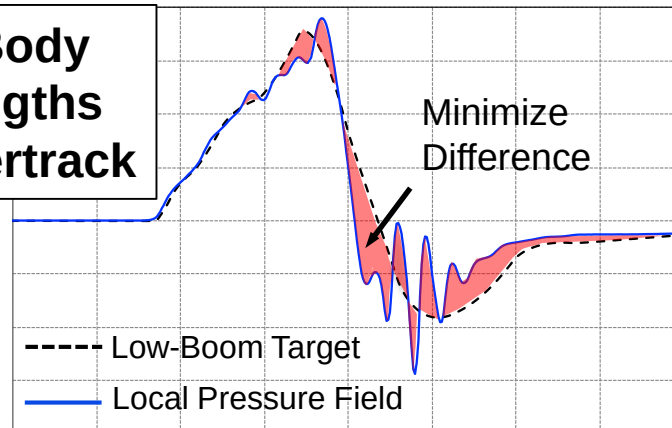
Optimization Problem

Minimize:
$$f = \sum_{i=1}^N \left(\frac{p}{p_{\infty}} \Big|_i - \frac{p}{p_{\infty}} \Big|_i^* \right)^2$$

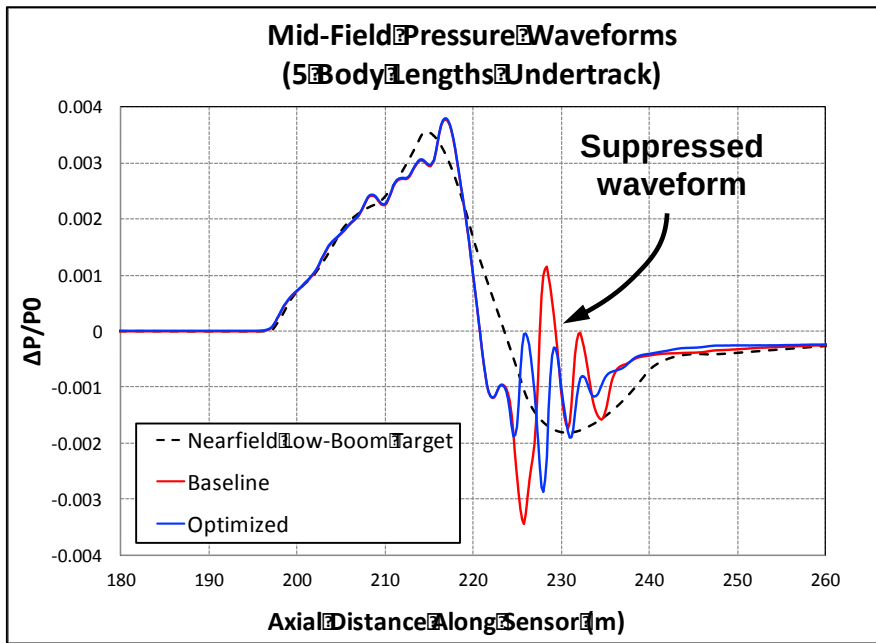
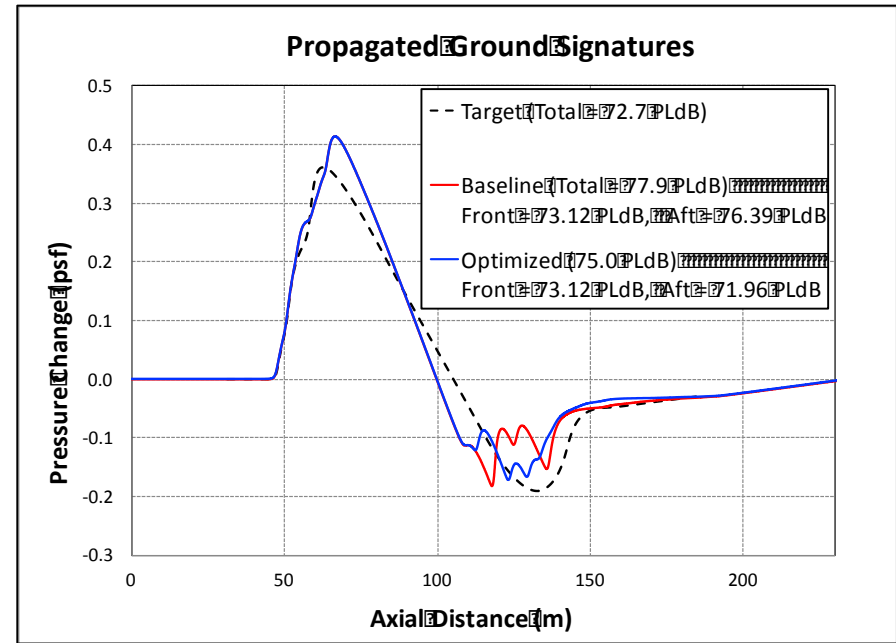
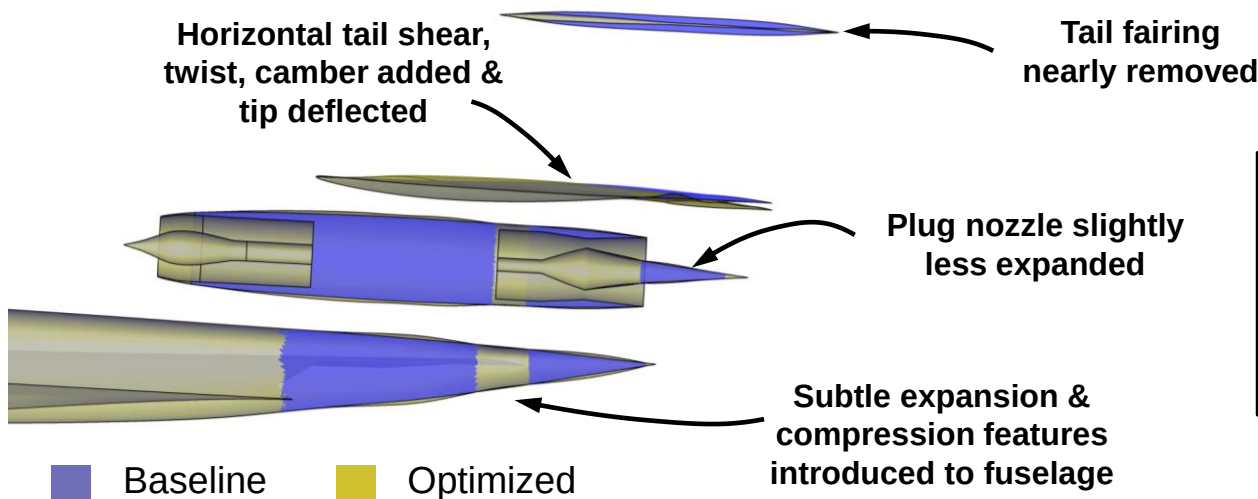
s.t.: $0.0 < C_D < C_{D,Limit}$

Local pressure ratio Target pressure ratio

5 Body Lengths Undertrack



Nearfield and Propagated Ground Signatures



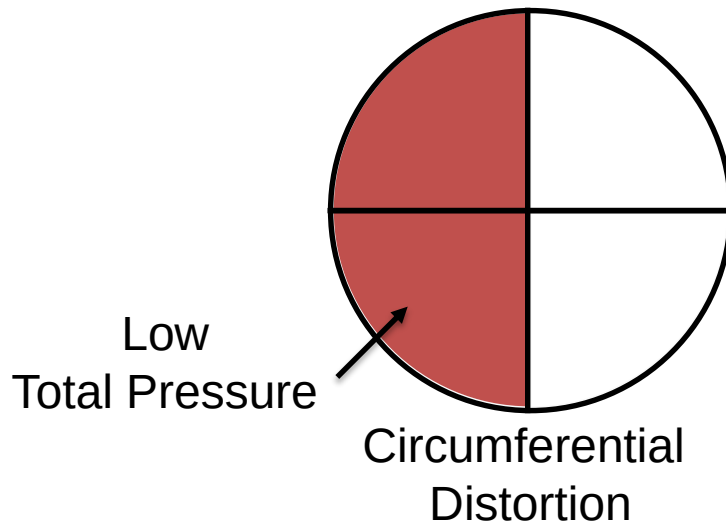
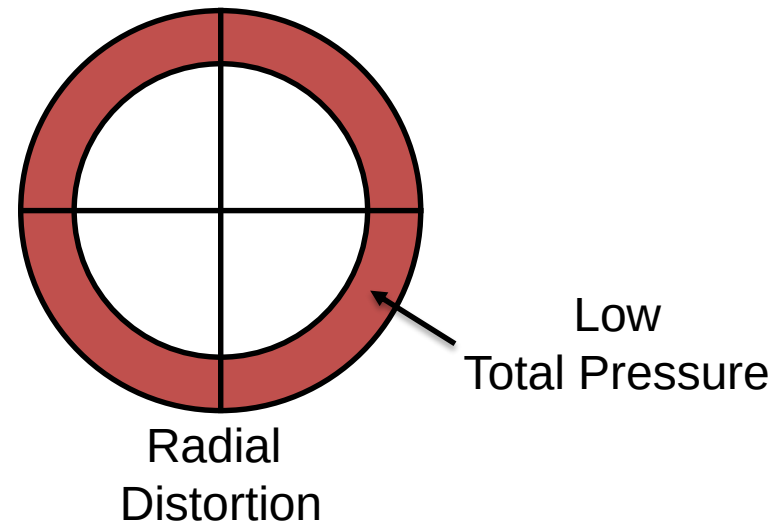
Aft signature perceived loudness reduced by 4.43 dB

Forward signature becomes dominant loudness source

Inlet Flow Distortion Subsonic Application



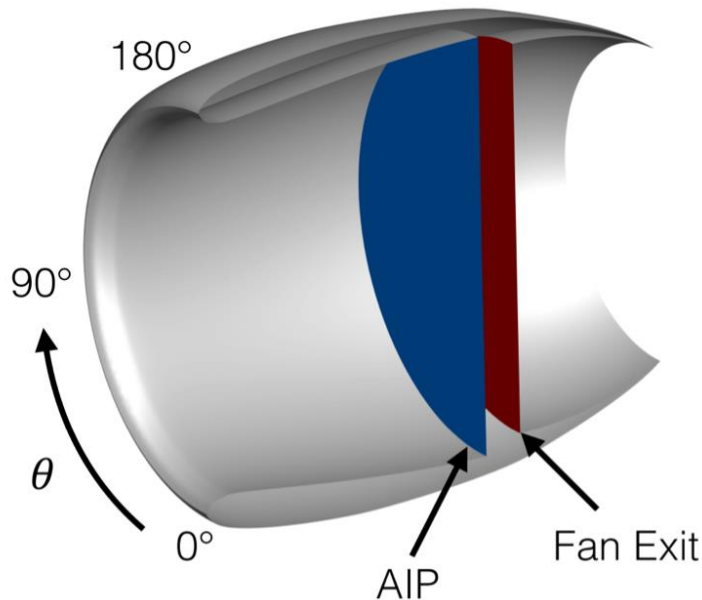
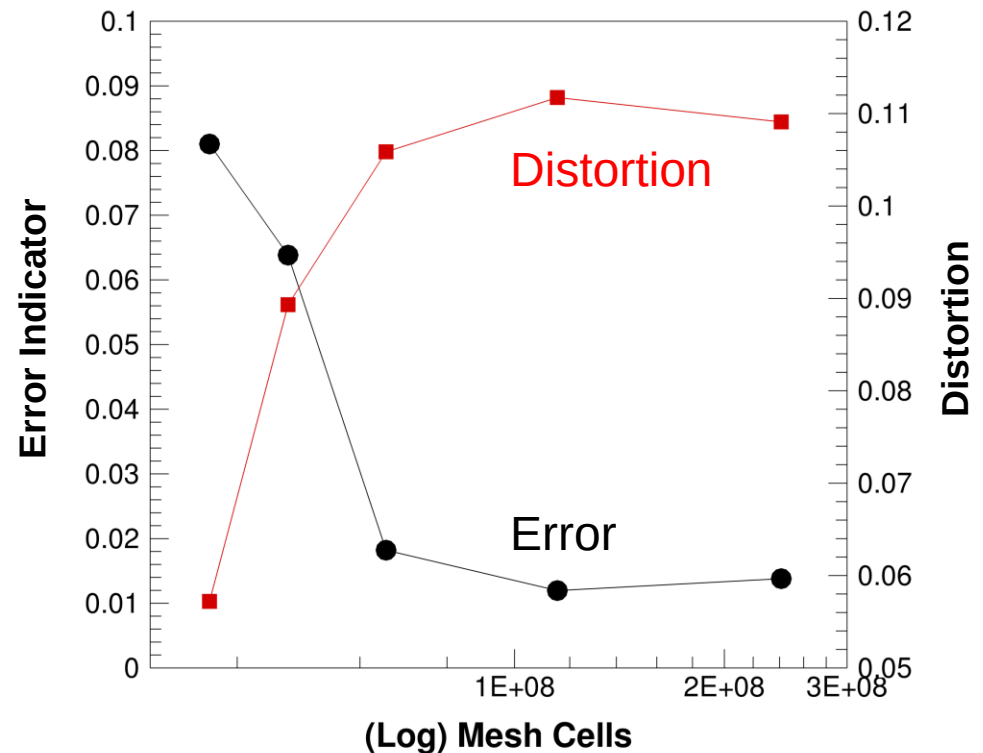
- Same tools are available for applications in subsonic flows (take off and landing)
- Circumferential distortion at the Aerodynamic Interface Plane (AIP) is minimized through adjoint-based optimization
- Sensitivity to grid refinement is reduced through adjoint-based grid adaptation
- AIAA 2017-3410



Adjoint-Based Mesh Adaptation



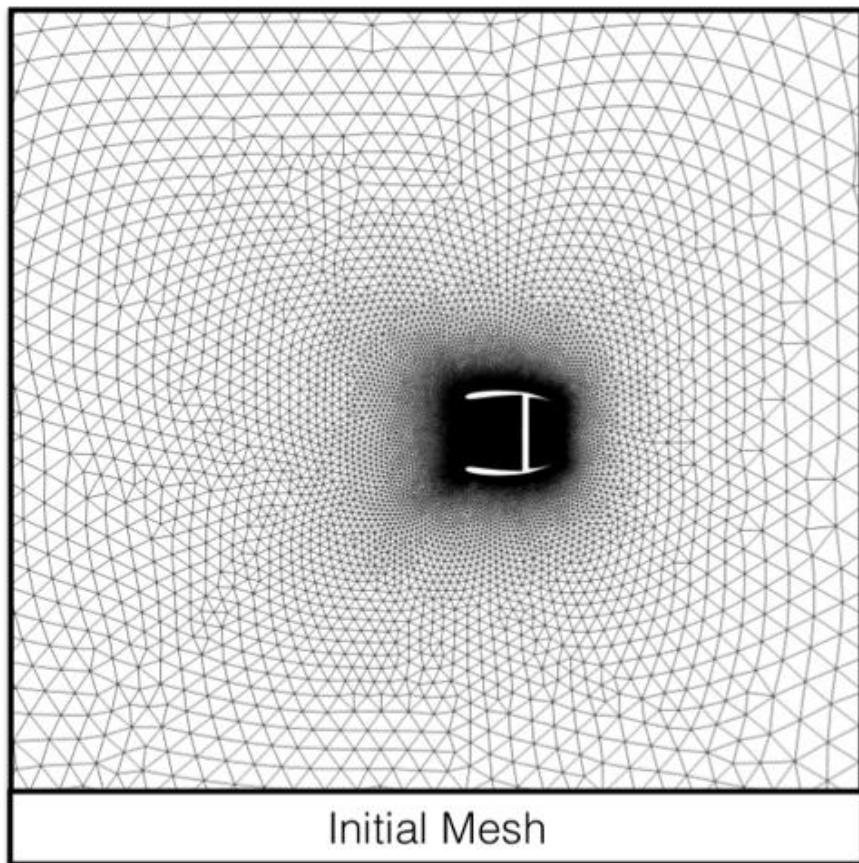
- Fan mass flow of 550 lbm/s
- Initial mesh size is 36.5 million tetrahedral cells
- 5 adaptation cycles with maximum element anisotropy restriction of 10
- Reduce the error in fan distortion calculation associated with mesh discretization
- **Distortion increases by 90% of the non-adapted mesh**



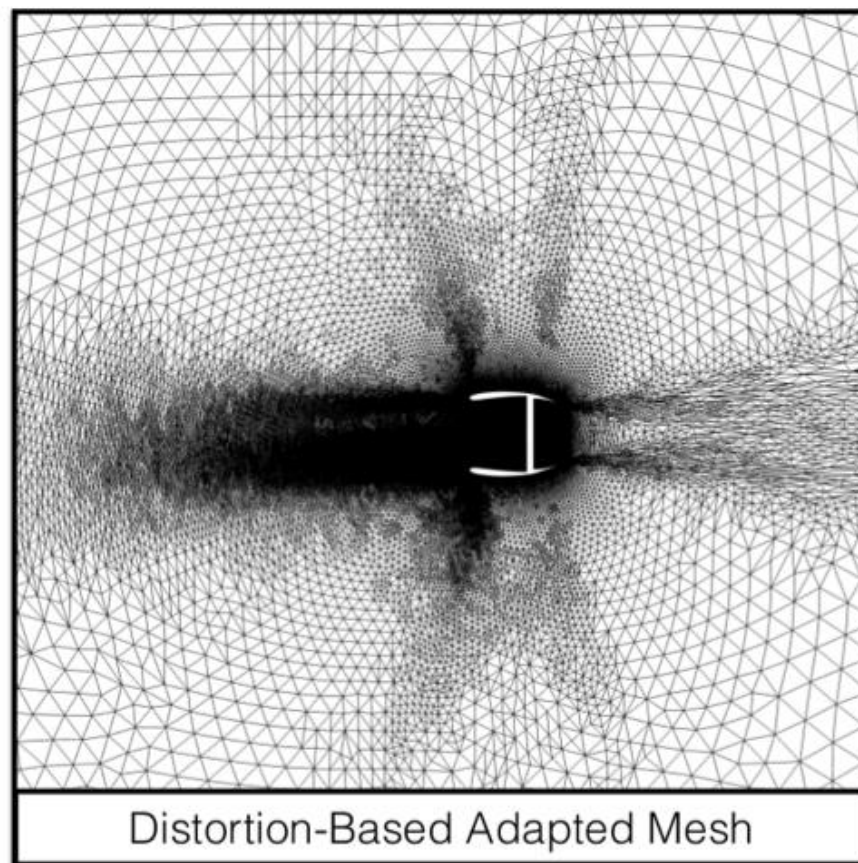
Adjoint-Based Mesh Adaptation



36.5 million tetrahedral cells



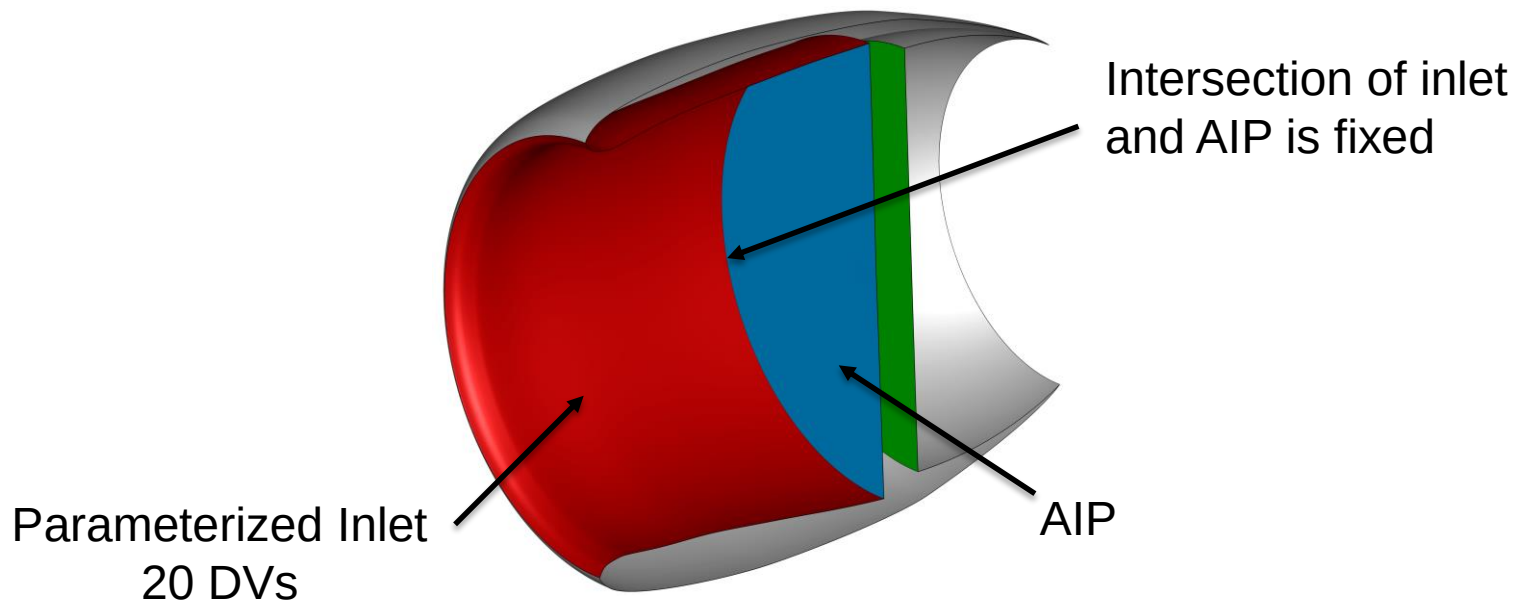
241 million tetrahedral cells



Verification of Design Optimization



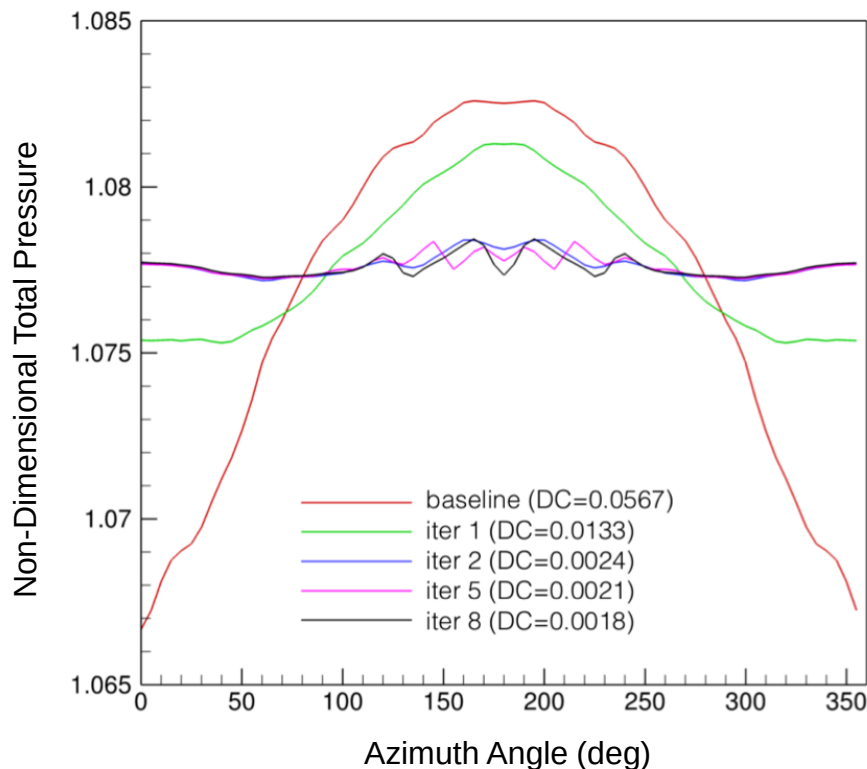
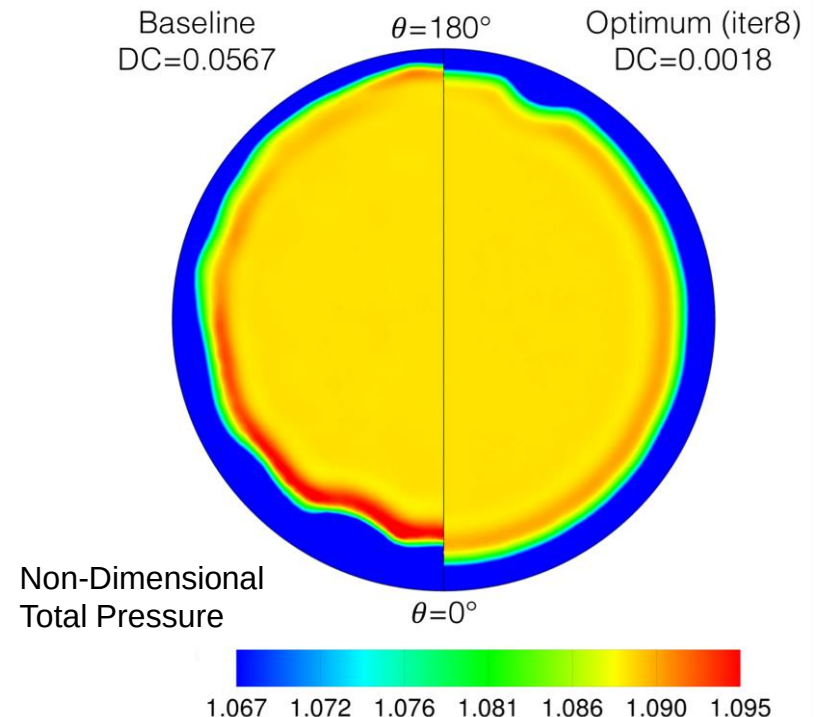
- Non-adapted half mesh consisting of 36.5 million tetrahedral cells
- Gradient-based Sparse Nonlinear OPTimizer (SNOPT)
- Free-form shape deformation tool (BANDAID) used to parameterize inlet
- 5 equally spaced sections along the longitudinal axis
- 4 design variables per section
- Design variables in each section equally spaced circumferentially in u - v space



Verification of Design Optimization



- Distortion for the final design (iteration 8) is 0.0018 (97% reduction)
- Distortion is significantly improved by design iteration 5
- Radial distortion may be addressed by the appropriate use of blade twist

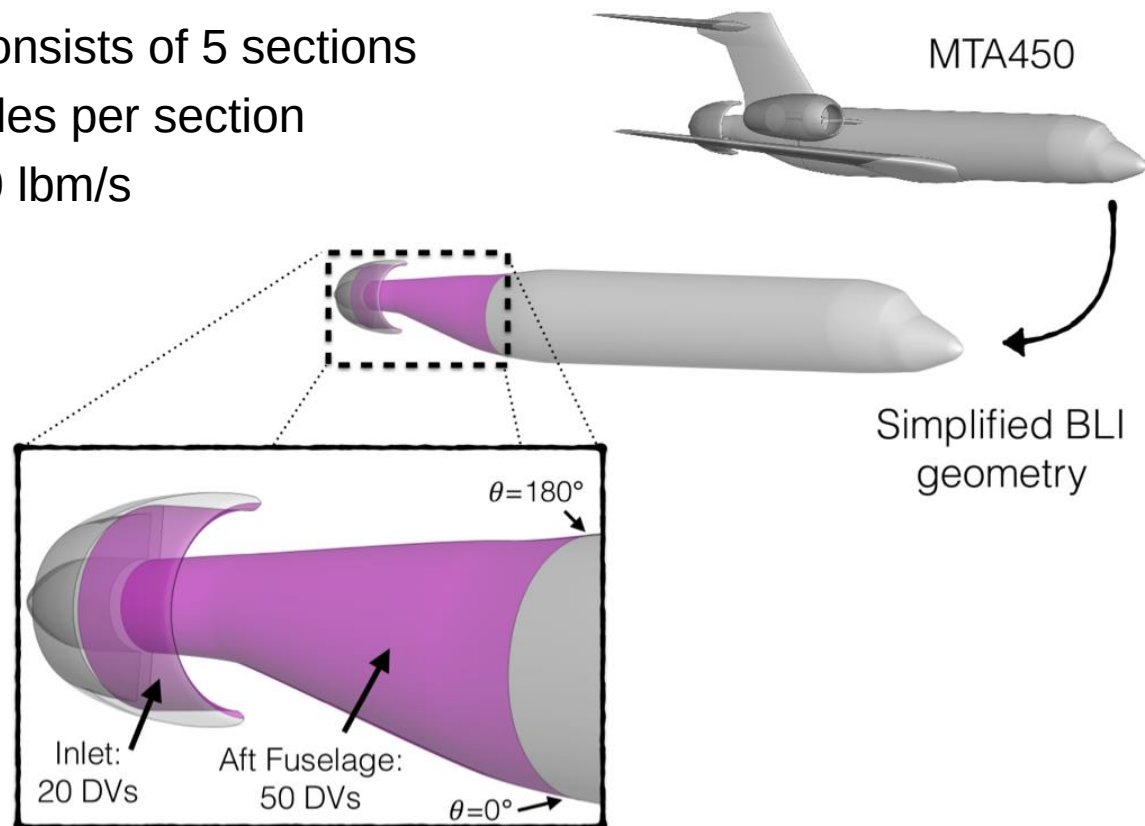


(DC = distortion)

Design Optimization of BLI Geometry



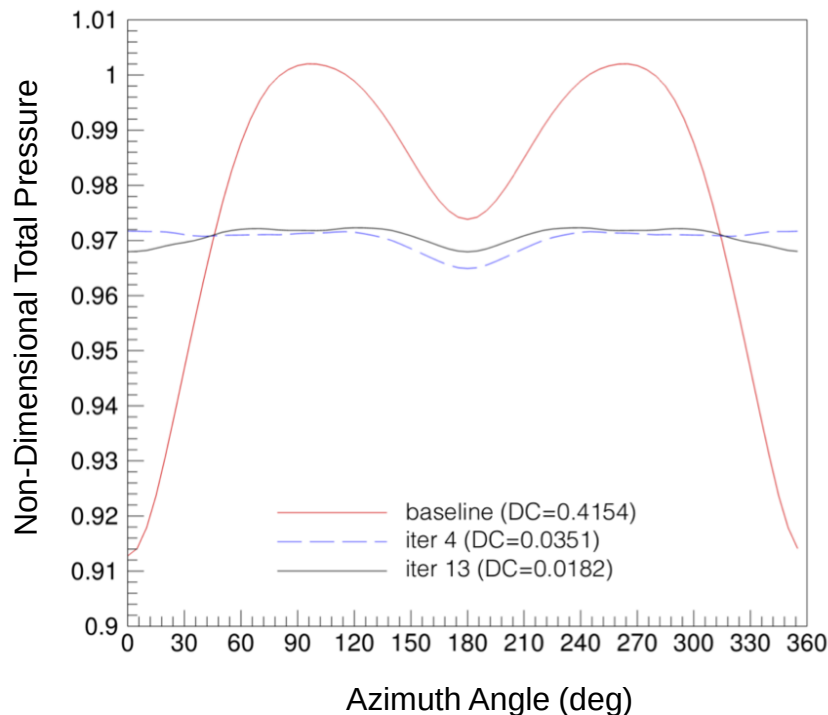
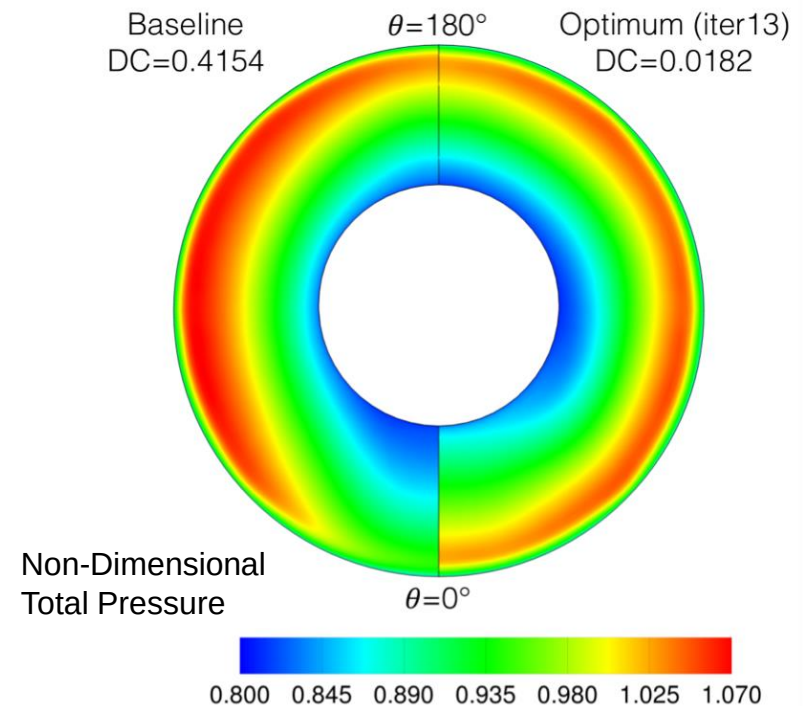
- Non-adapted symmetric half mesh consisting of 21 million tetrahedral cells
- 516 processor cores on dual socket hex core 2.80 GHz Intel X5660 Westmere
- Computation time of each CFD solution and adjoint calculation was 15 min
- Total wall time for entire optimization (13 design iterations) was 7 hours
- Same inlet parametric scheme as before
- Aft fuselage region consists of 5 sections and 10 design variables per section
- Fan mass flow of 450 lbm/s



Design Optimization of BLI Geometry



Parameter	Baseline	Optimum (iter 13)	Change
Distortion	0.4154	0.0182	-95.6%
Worst distortion sector (deg)	348	276	
Pressure recovery	0.87	0.86	-1.1%
Drag force from fuselage and nacelle cowl (lbf)	1,584	1,815	14.5%
Drag force from fuselage, nacelle, inlet, and nozzle (lbf)	3,912	3,936	0.62%

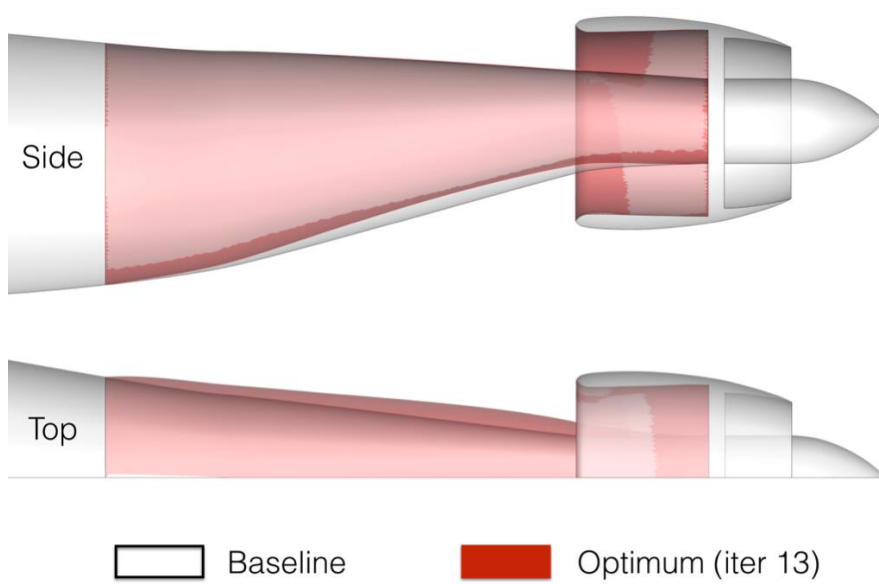
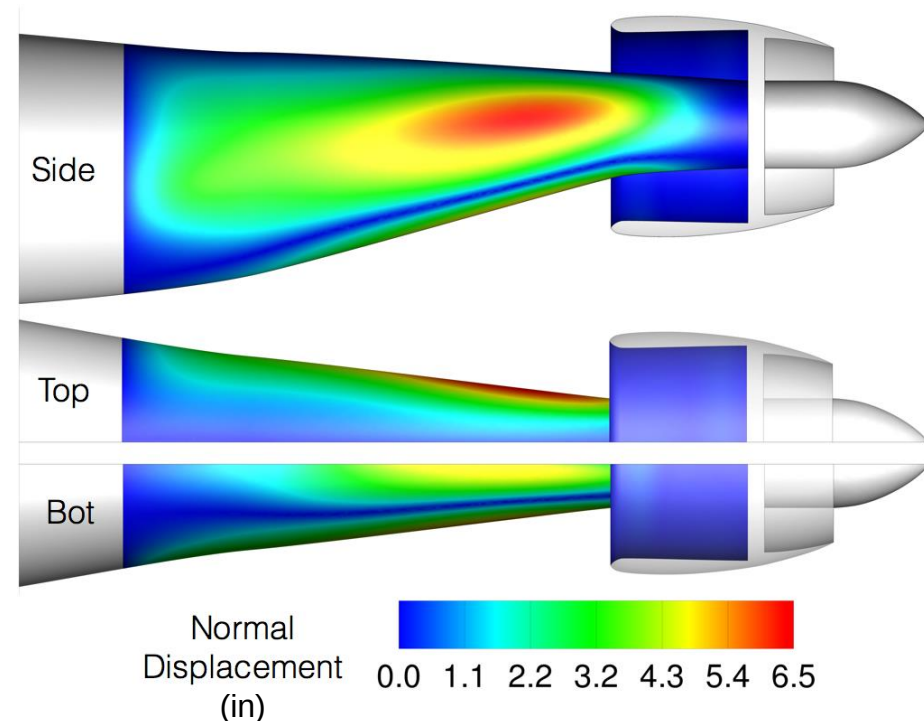


(DC = distortion)

Design Optimization of BLI Geometry



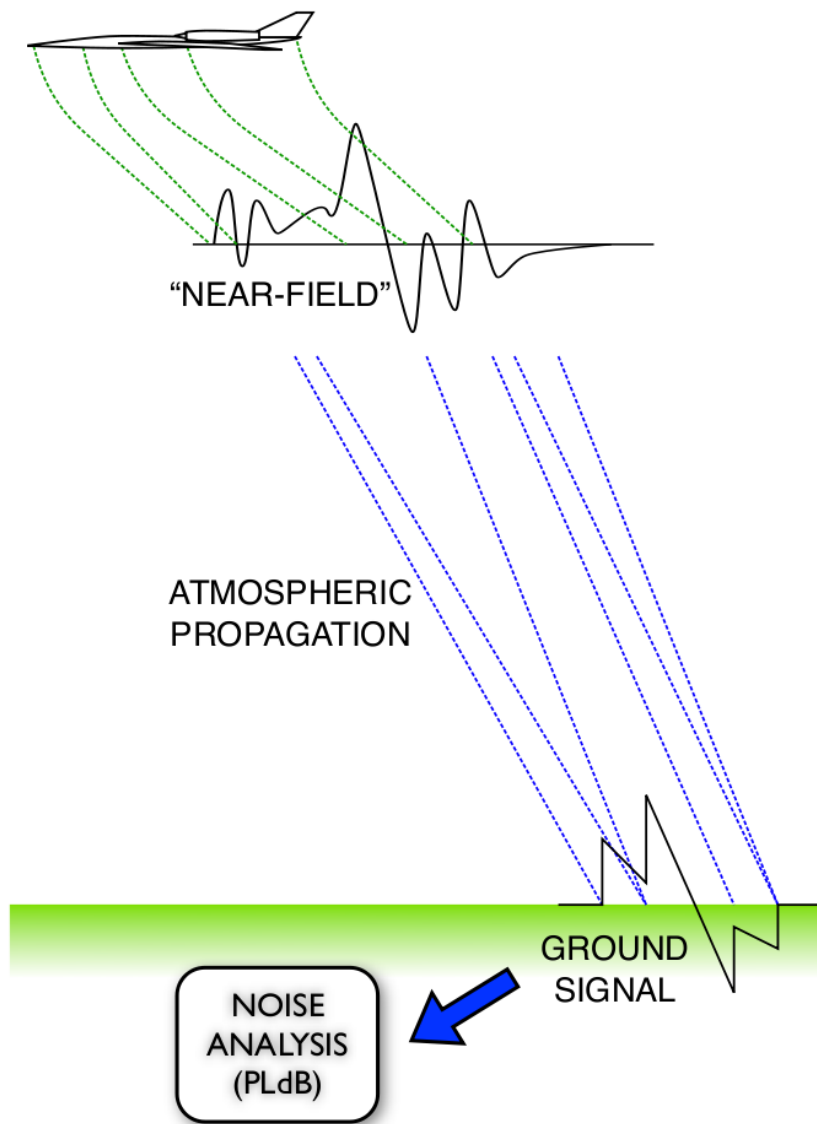
- Normal displacement for the optimized geometry relative to the baseline geometry
- Maximum displacement of shaped geometry is 6.3 in and occurs at approximately $\theta=90^\circ$ in the aft fuselage region
- Maximum displacement of inlet is 0.42 in and occurs at $\theta=0^\circ$



Sonic Boom Prediction Workshops (SBPW)

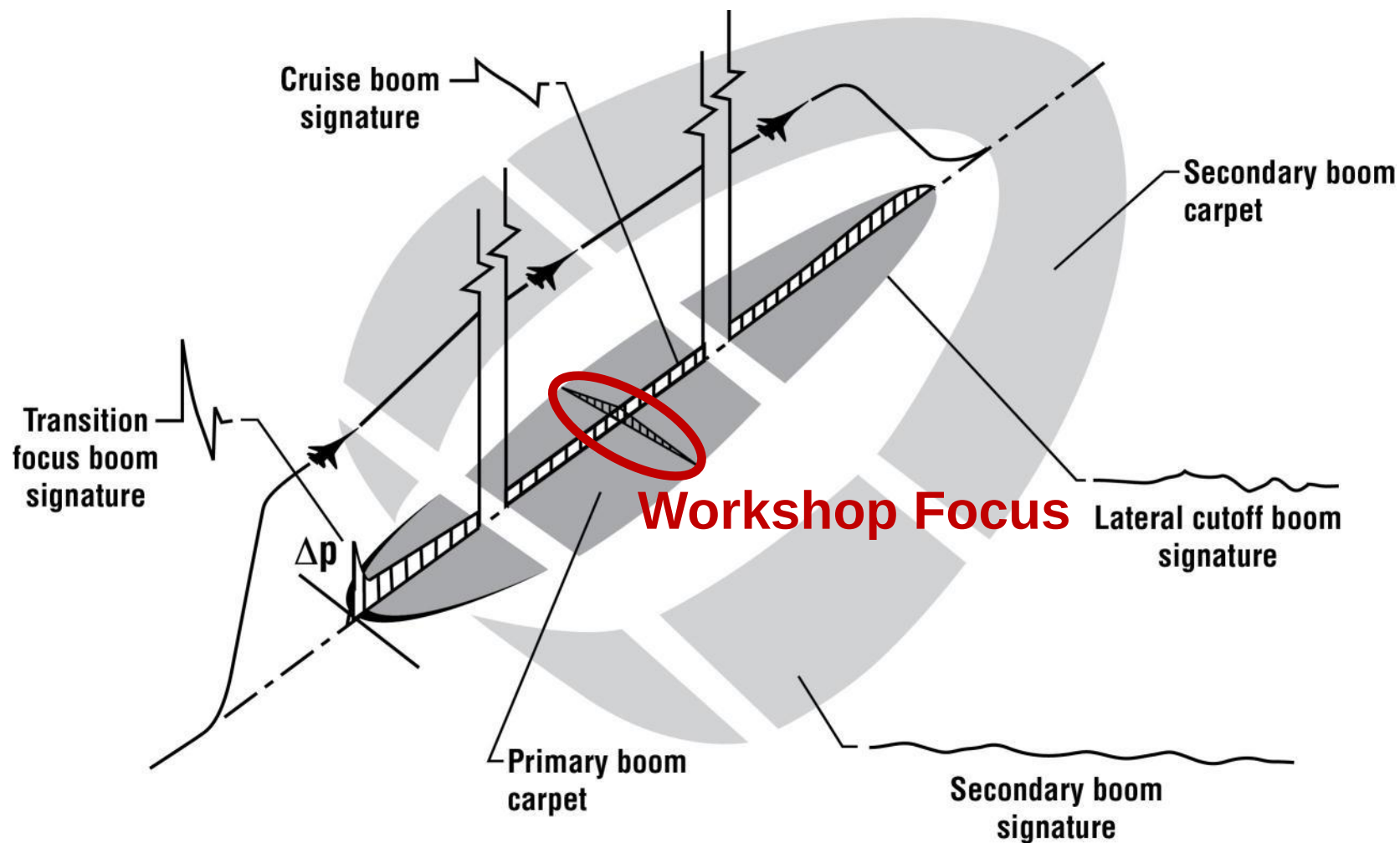


- Assess nearfield Computational Fluid Dynamics (CFD) as part of sonic boom prediction
 - Propagation assessment included in the second workshop
- Impartially compare relevant measures of nearfield signatures to each other and wind tunnel measurements
 - Includes uniform application of propagation and noise measure calculation
- Following American Institute of Aeronautics and Astronautics (AIAA) workshop model
 - Drag Prediction (Cruise)
 - High Lift Prediction (Takeoff and Landing)



[Wintzer, PhD Thesis, Stanford, 2012]

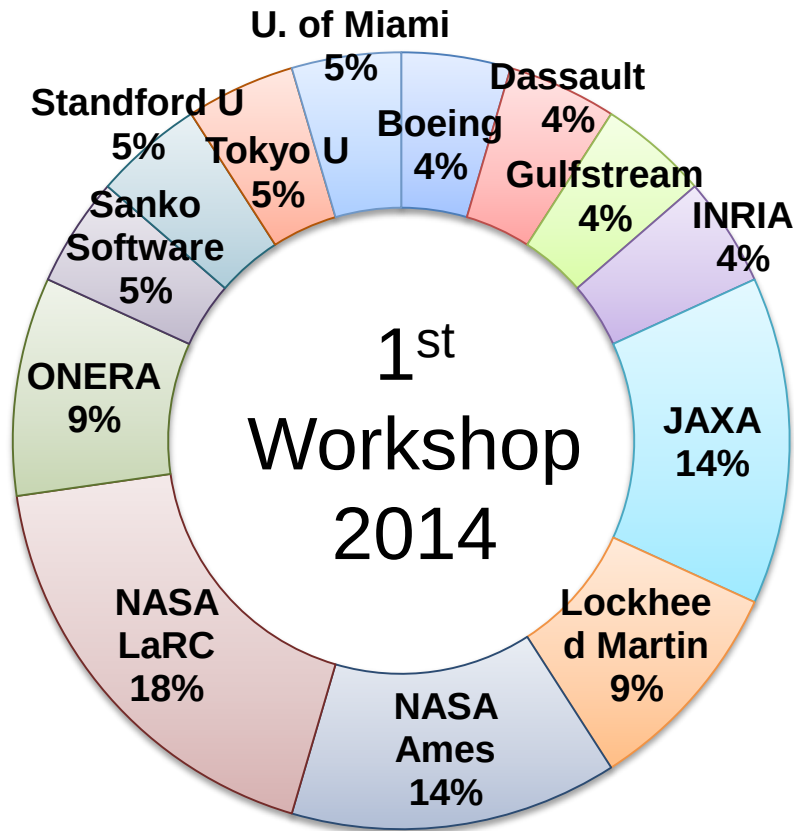
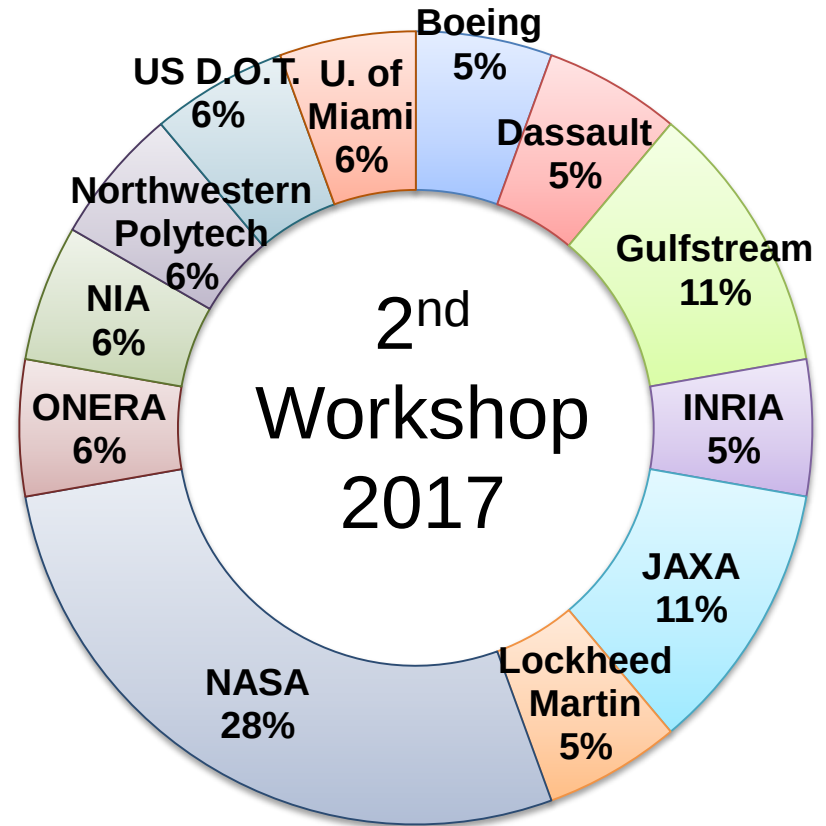
Typical Mission Boom Carpet



AIAA Sonic Boom Workshop Participants



- Approximately 50 attendees at both workshops and participants from:



First AIAA Sonic Boom Workshop Models



- Focus on models with available nearfield wind tunnel measurements



Optional

LM1021 Full
Configuration

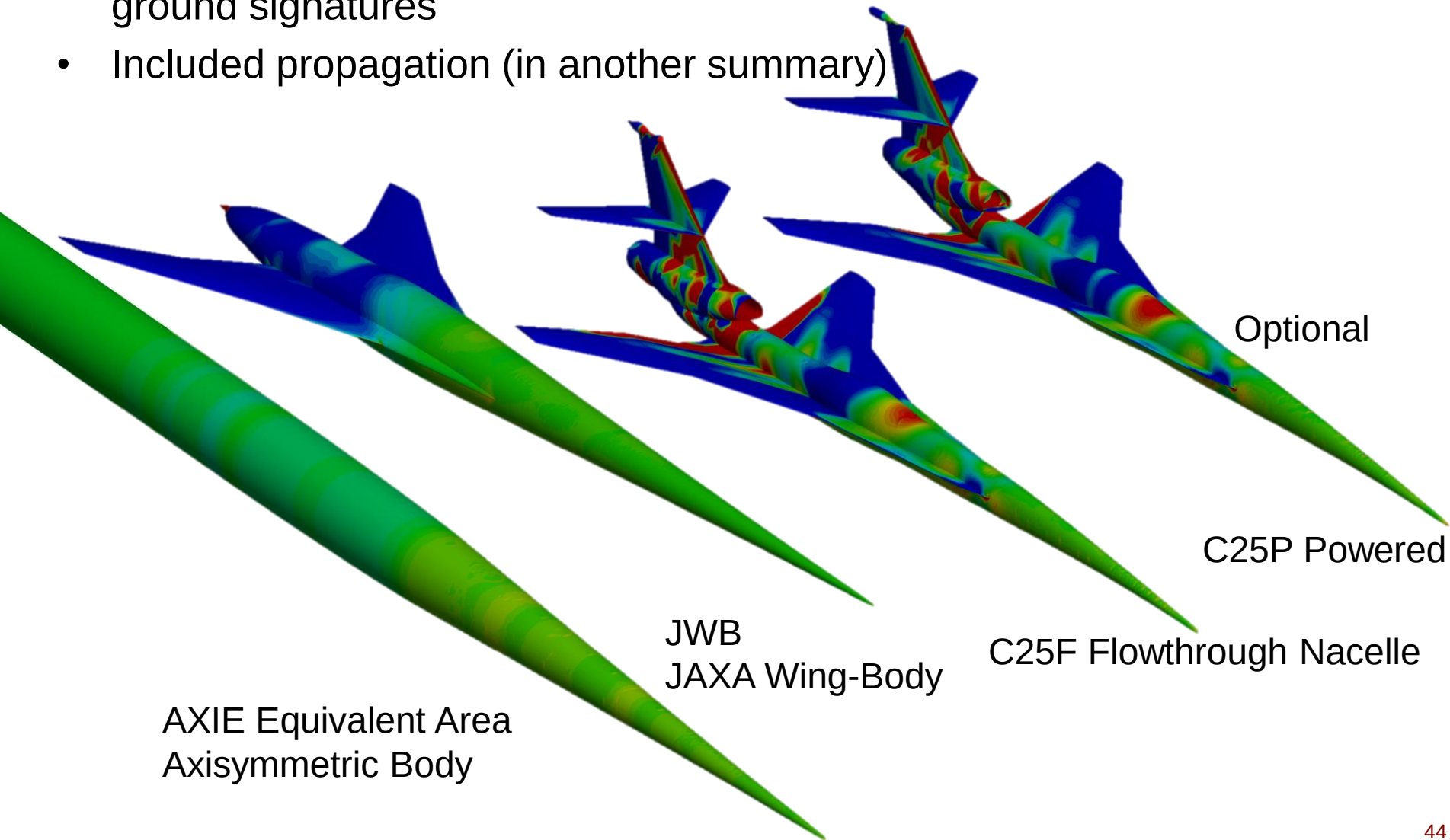
Simple Delta Wing Body

Flat-top signature
axisymmetric SEEB-ALR

Second AIAA Sonic Boom Workshop Models



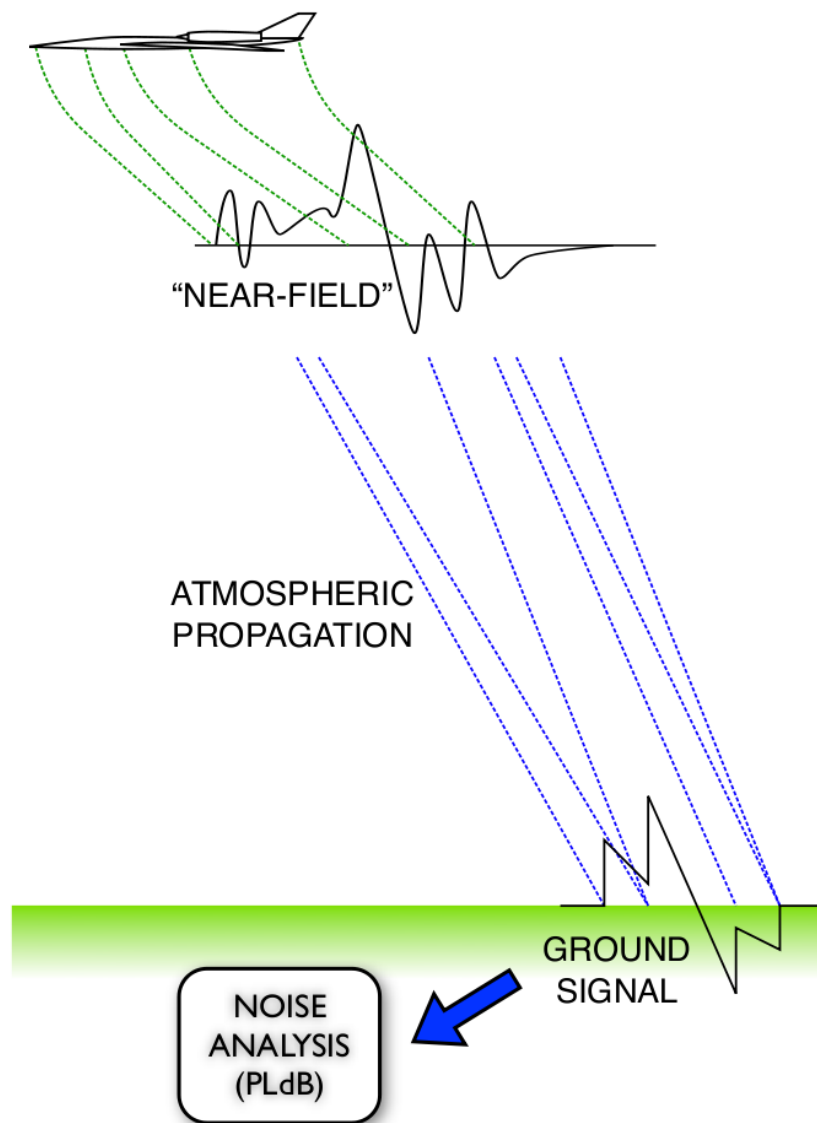
- Focus on a range of model complexity with similar nearfield and ground signatures
- Included propagation (in another summary)



Workshop Analysis Procedure

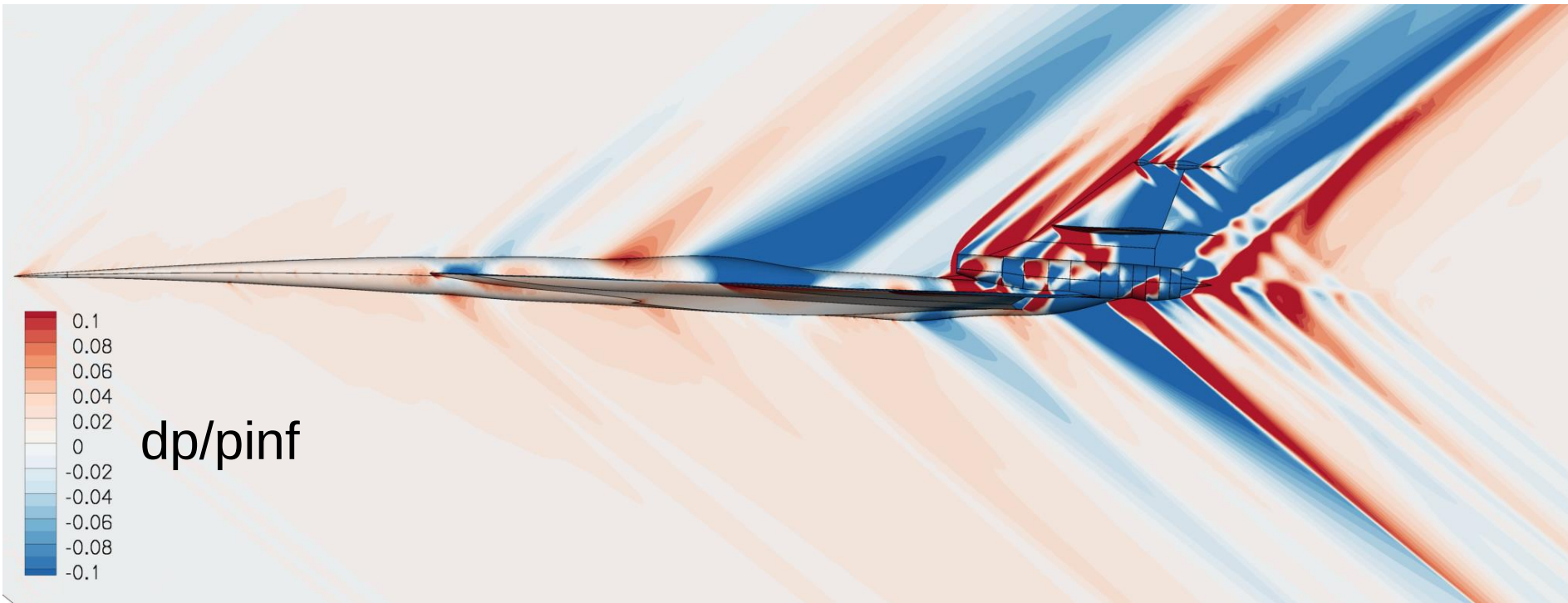


- Nearfield CFD signatures provided by participants
- Propagation through standard day atmosphere by committee
- Calculation of Stevens JASA (1972) Perceived Level (PL) by committee
- Illustrated with the second workshop cases before comparing levels and variation

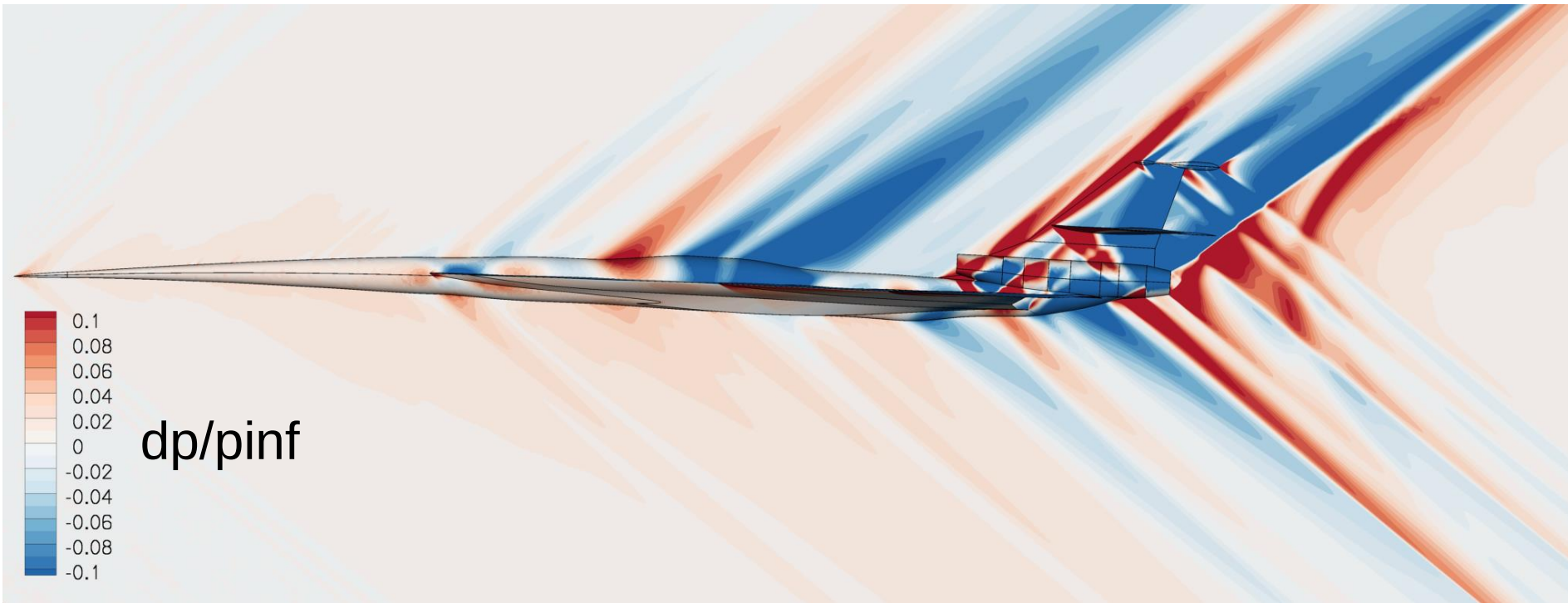


[Wintzer, PhD Thesis, Stanford, 2012]

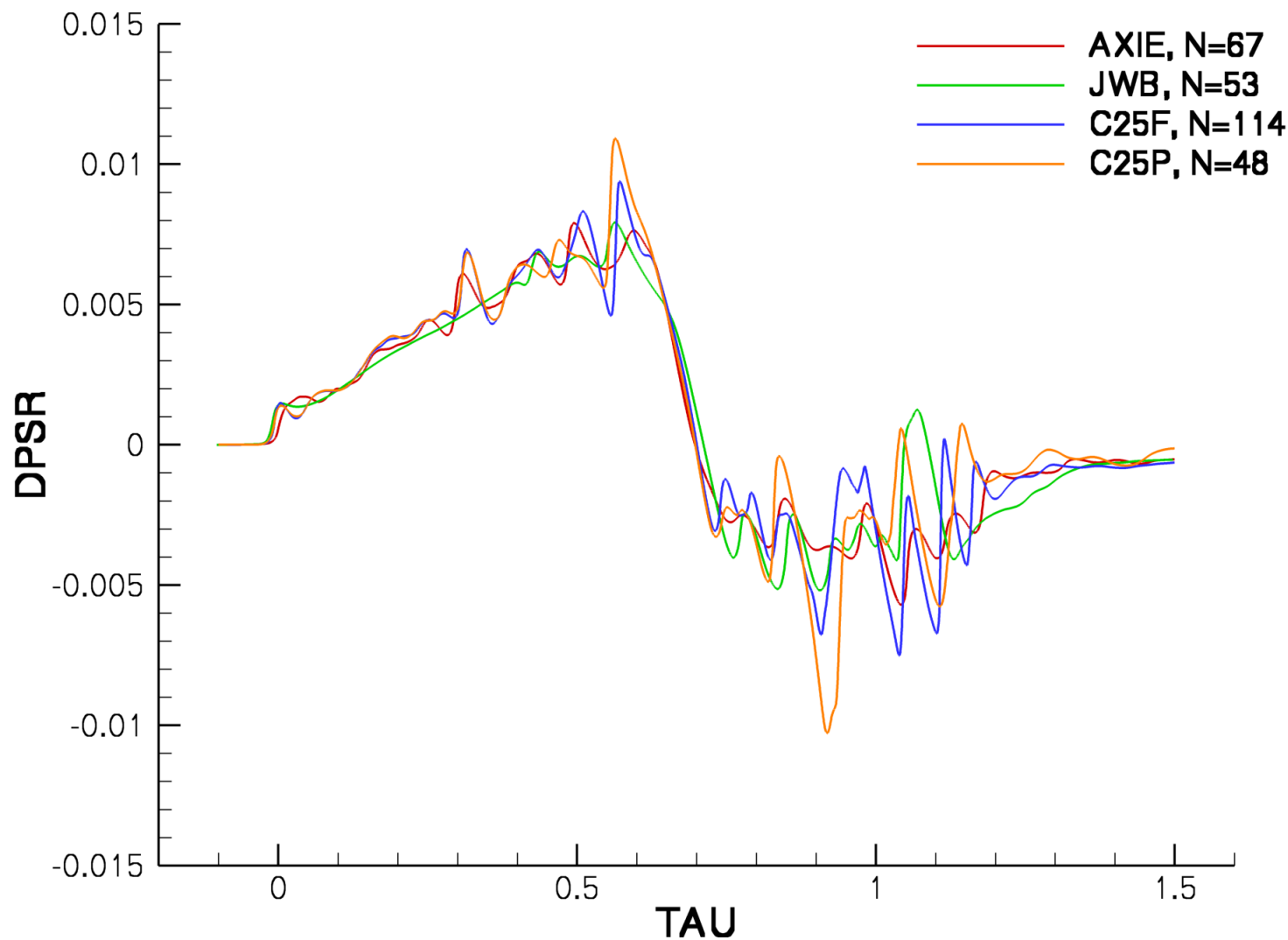
C25P Powered Pressure Disturbance



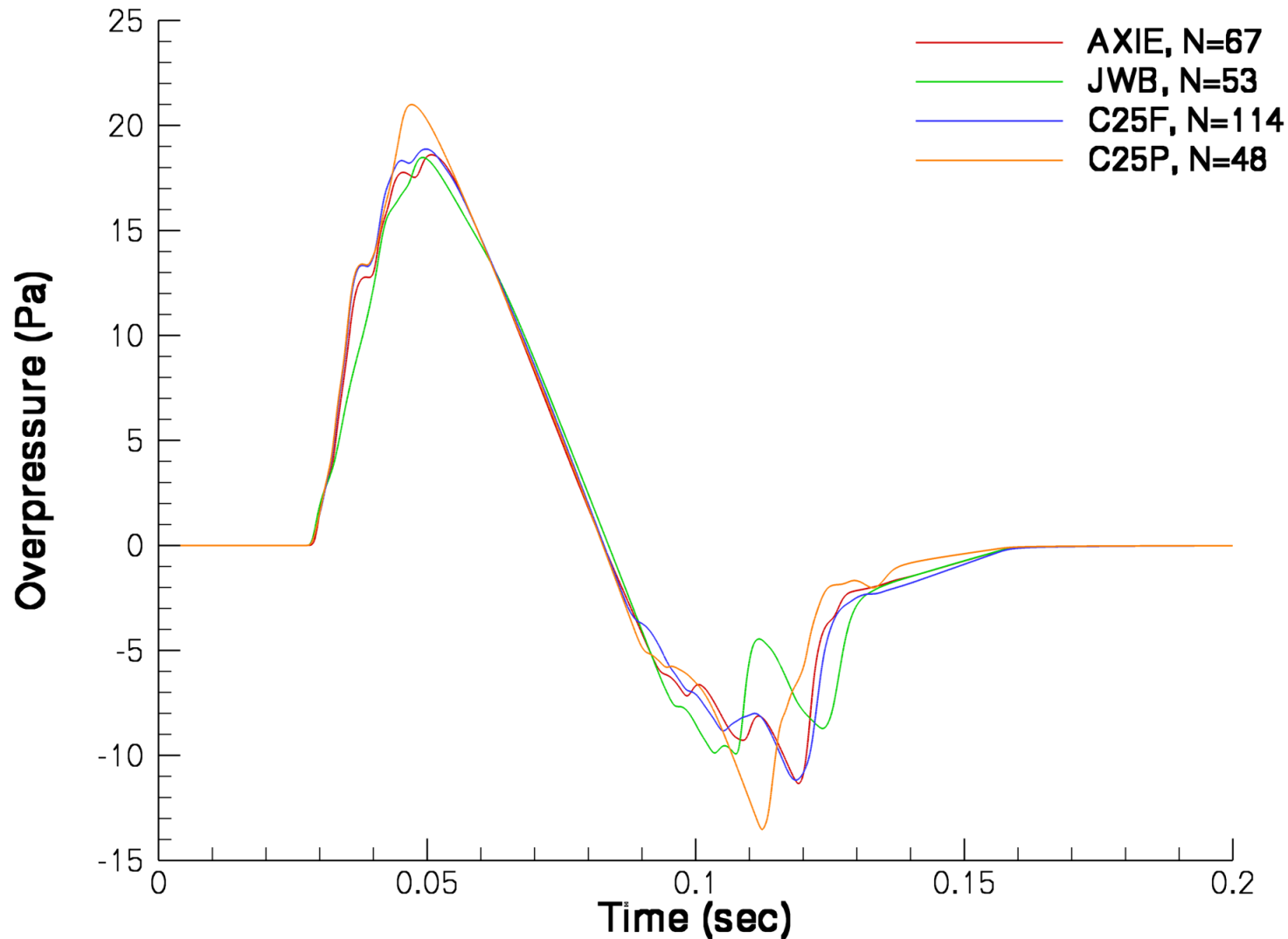
C25F Flowthrough Pressure Disturbance



Nearfield Ensemble Mean $R=3$, $\text{PHI}=0^\circ$



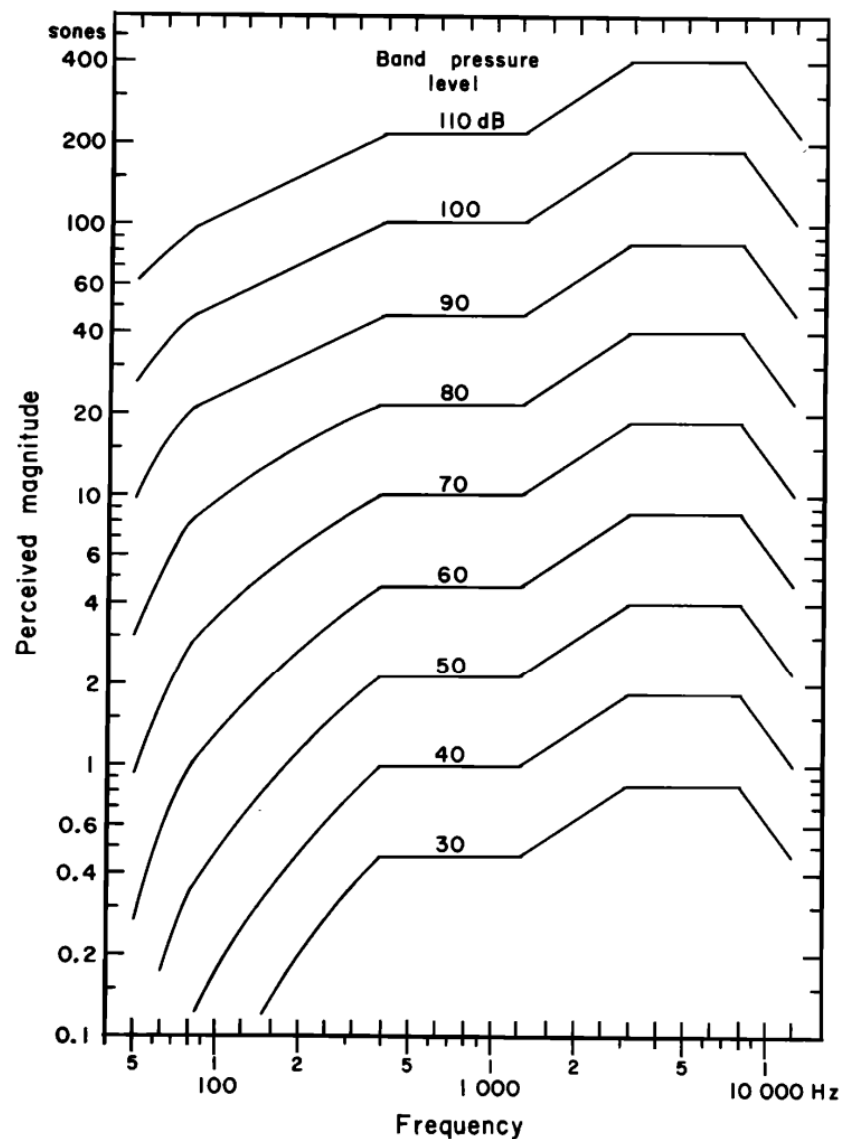
Ground Ensemble Mean R=3, PHI=0°



Perceived Level (PL)



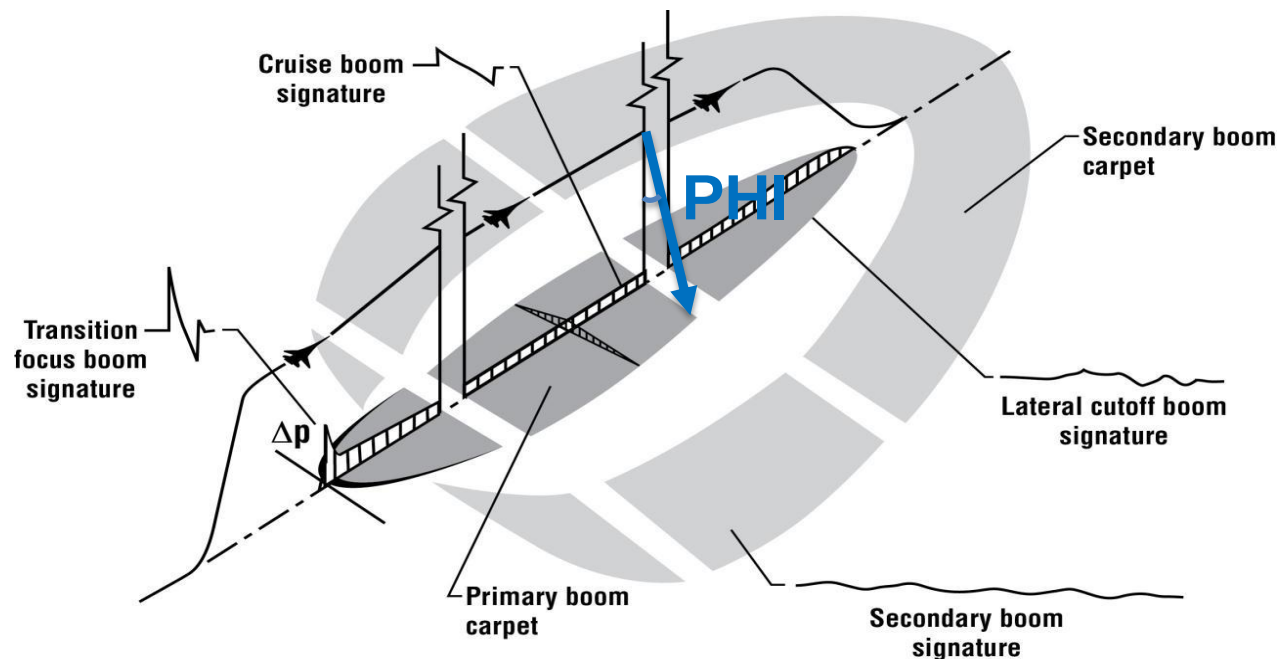
- Signature sound pressure level is gathered into 1/3 octave bands
- Band levels are converted into sones (loudness)
- Sones from each band are combined
- Sones are converted into PL via logarithm



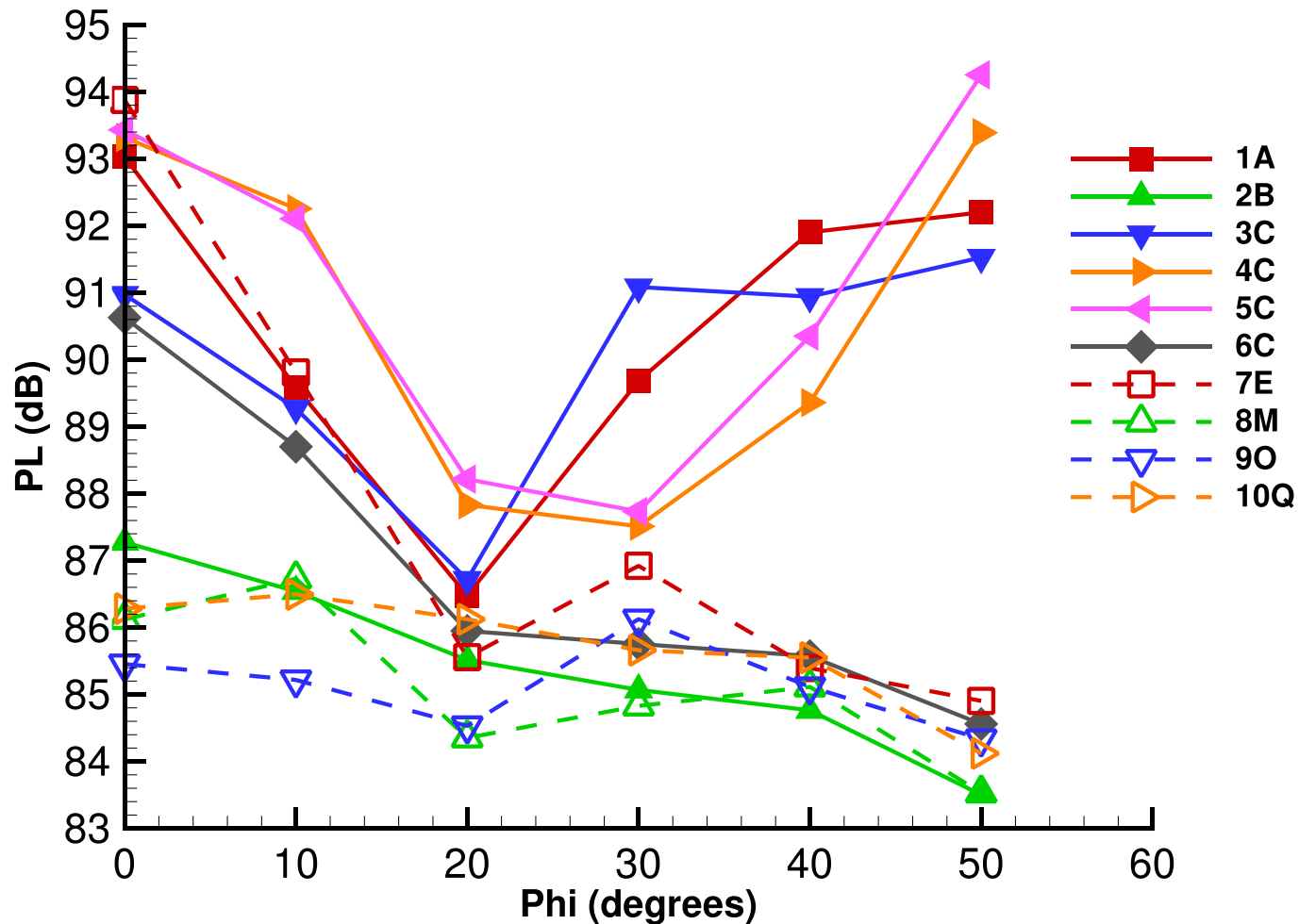
Progress Between SBPW1 and SBPW2



- Complex case had more submissions and less variation
 - Statistics available for required full configuration that was optional in the first workshop
 - Optional propulsion boundary condition case was added
 - Median loudness quieter and therefore more difficult to predict



SBPW1 LM1021 PL Carpet, R=3.1

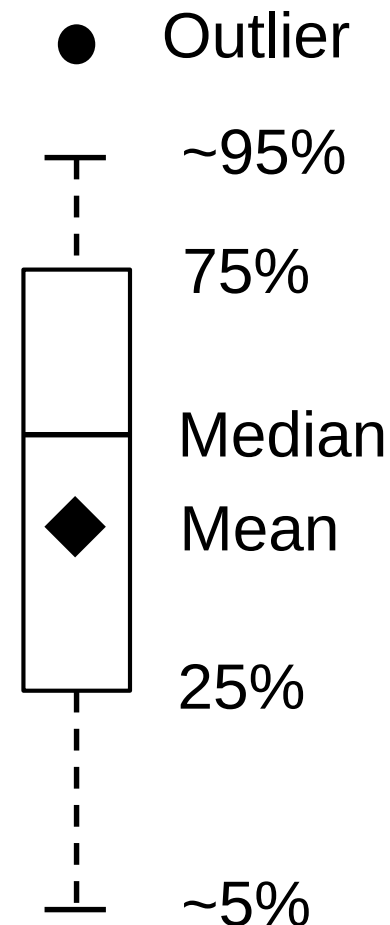




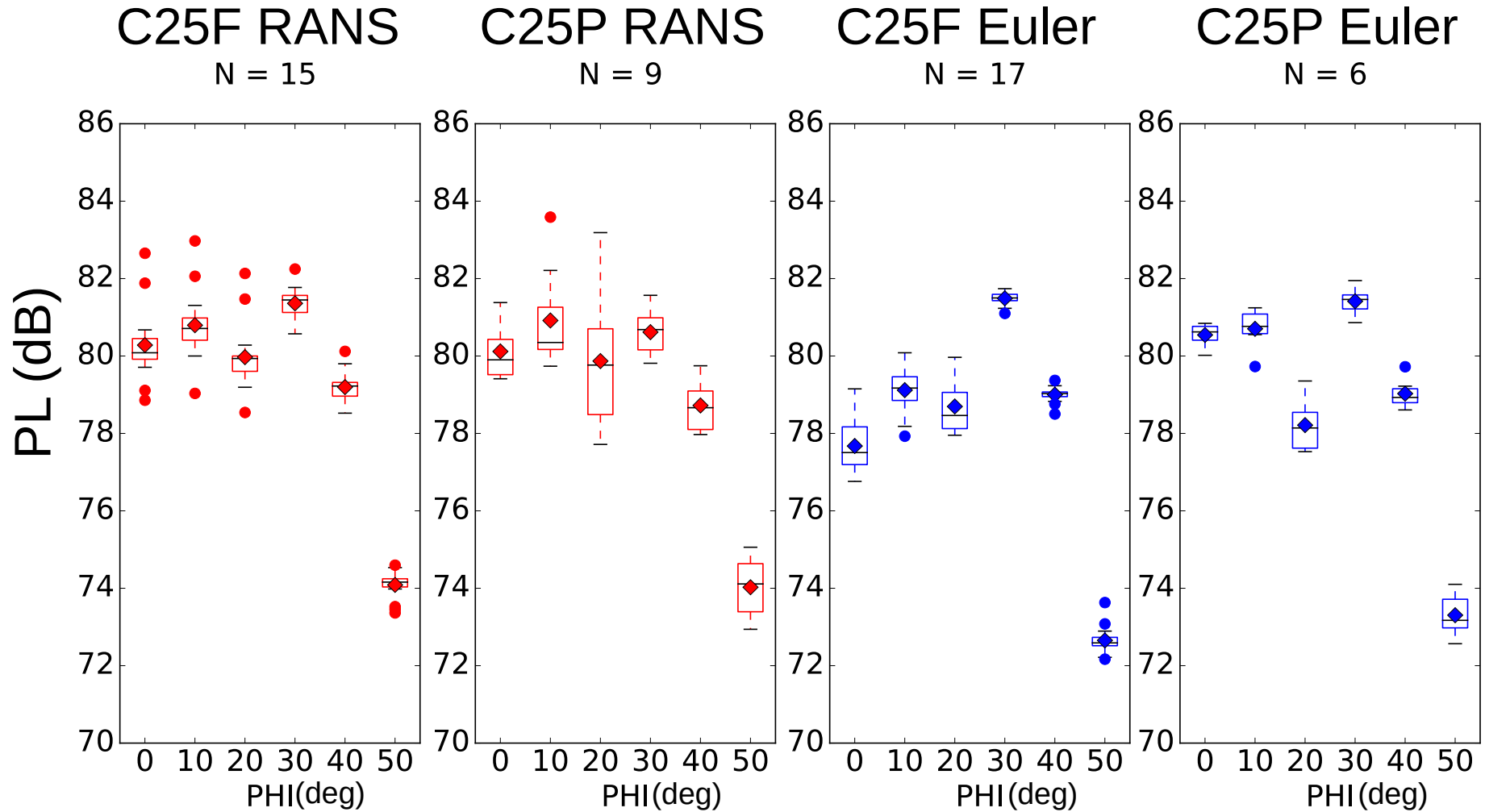
Box and Whisker Plot Descriptive Statistics



- Steven's Perceived Level (PL) computed from ground signatures
- Goal is to identify “different” results, not “correct” or “wrong”
- Quantify observed variation between predictions
- Box (half of submissions) and whisker plots (95% coverage for normal distribution)
- Used by AIAA Drag Prediction Workshop (AIAA 2017-1209)



C25F and C25P from R=3



- Sonic boom prediction tool chain described
- Forward and adjoint sensitivities are available for error transport, grid adaptation, and design optimization
- Examples provided to demonstrate this capability with propulsion integration effects
- Prediction variation of a group of international participants on a relevant configuration obtained via statistics
 - Powered boundary conditions had similar level of variation as a flowthrough nacelle in the second workshop (both lower than first workshop)
- Supersonic concepts with acceptable performance and environmental impact (sonic boom) with estimated uncertainties may provide information to regulators to assist in the establishment of a sonic boom certification standard

- Visit <http://lbpw.larc.nasa.gov> for
 - Presentations and references (AIAA Low-Boom Special Sessions)
 - Geometry, grids, submitted data, and derived data are available: **independent analysis encouraged!**
 - Sign up for the low-traffic announcement e-mail list
- Planning underway for next workshop (2020)
 - Lower PL configurations from lower 80s/upper 70s to middle 70s
 - Include propagation and noise metric experts
 - Reaching out to the Uncertainty Quantification (UQ) community

